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WELDING METALS BY FRICTION

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by

V.I. Vill'

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The book is calculated to meet the needs of engineers and industrial workers concerned with metal welding problems. It may also be used by university students and technical school students who specialize in welding.

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TABLE OF CONTENTS

ABSTRACT

Welding metals by friction. Vill', V.I., izd-vo "Mashinostroyeniye", 1960, 176pp, 13 tables, 90 illus., 80 bibliographic entries.

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As an improvement over the first edition (1959), this edition examines the bases of the theory of the friction welding process, and the experience of foreign and domestic firms in friction welding is presented.

The book is calculated to meet the needs of engineers and industrial workers concerned with metal welding problems. It may also be used by university students and technical school students who specialize in welding.

INTRODUCTION

The partial conversion of mechanical energy into thermal, which always accompanies the friction process, has been known for a long time. In a great majority of cases the liberation of the heat during friction was considered to be a harmful phenomenon. The technology continuously fights against this phenomenon. There is only a very small number of examples where heat liberation is beneficial. One of these examples is the use of friction heat for the welding of metals.

Numerous cases of welding of the shaving to the cutting tool or the tail stock of the lathe to the part being worked on, or the axis collars of railroad cars to the bearings of the axle box, etc. were known for a long time in the practical metal processing. In addition, purposeful attempts of friction welding of metal rods on a lathe were also known. However, these attempts, which were in many cases successful, were considered as technical curiosities and no serious technical significance was ascribed to them. References on the basic possibility of friction welding of metals can be encountered in literature (5,47,50). These references are stingy and rare. Not so long ago a patent for friction welding was discovered which was taken out at the end of the last century (66). However, the friction welding was not utilized in practice. This is due, apparently, to the fact that friction welding received a negative evaluation, supported for a long time by scientists.

Only in 1956, the welder-innovator A.I. Chudikov overturned this prevalent view by conducting a series of experiments. His great service is not that he "discovered" the friction welding, as many people think, (as is evident from the above, friction welding was known before him) but that he laid the foundation for the practical use of friction welding by being convinced

himself of the possibility of obtaining good quality steel rod joints by friction heating. The innovator was supported wholeheartedly at the All-Union Scientific Research Institute of Electrical Welding Equipment (ASRIEWE). The studies conducted by us at the ASRIEWE confirmed the results obtained by A.I. Chudikov. For the first time, the erroneous notions on deficiency [1] in the welded joints done by friction heating were disproved by these studies. These studies helped to reveal very important and interesting physical features of the friction welding process. Its advantages were laid bare. In connection with this, a special laboratory was organized at the ASRIEWE for further studies and perfection of this new welding method, for the development of the equipment, and for introduction of friction welding into production.

As a result of acquainting the scientific community at meetings and conferences with the work of the friction welding laboratory at the ASRIEWE and publishing first in the institute publications and then in the official press during 1956-1957, the advantages of friction welding came to the attention of numerous industrial enterprises and scientific research organizations, which joined in the study of this method, its development and its wide use.

Among the number of these organizations and enterprises are: Minsk Tractor Plant - the pioneer in introduction of friction welding on a large scale in continuous mass production, Chelyabinsk and Altay Tractor Plants, NIItraktosel'khozmash, the Altay Metallurgy Institute of the Academy of Sciences of USSR, TSNIITmash "Frezer" plant, Chelyabinsk NIPTIAMmash, Kharkov Polytechnic Institute, and several others.

Now friction welding is successfully used at more than 150 industrial enterprises of the Soviet industry. With its help,

a series of complicated and very essential practical problems were solved. The operating equipment pool for friction welding yields now more than 5,000,000 rubles annually in savings. This will be continuously increased with the introduction of new machines into operation.

The work performed in the Soviet Union in the field of friction welding served as incentive for its development abroad. A series of firms in the USA, England, France, Japan, Federal German Republic began to conduct studies and design equipment for "Russian" welding, as friction welding is often called abroad. This underlines the fact that the birthplace of friction welding study and use is the Soviet Union.

Further friction welding studies in the USSR are conducted together with organizations and enterprises in the German Democratic Republic, Poland, and Czechoslovakia. The aim of these studies is a more rapid and efficient utilization of friction welding.

As a result, at present time, significant experience in the industrial utilization of friction welding has been accumulated in the various branches of industry. Many Soviet and foreign studies of applied as well as theoretical nature were published in the world literature. Apparently, there is need to systemize and to generalize this experience because of the apparent advantages of friction welding, the growing interest in friction welding, and the continuously growing volume in the application of friction welding. The generalization is directed to even larger utilization in our country of this progressive welding method.

The first edition of this book (1959) was quickly sold out. It is a bibliographic rarity. In 1961 it was translated into

English and published in the USA. In 1967 it was published in the Federal German Republic in German. This confirms the importance of the material discussed in the book.

In the present second edition the book was significantly reworked, enlarged, and completed with most recent data. The author hopes that this new edition will more than the previous edition help in solution of problems discussed above.

As any other work, this book, of course, is not free from deficiencies. The author is thankful in advance to all organizations and persons, who by their response and suggestions will help to eliminate these deficiencies in the future.

1. It was thought earlier that the heat liberated during friction is not sufficient for welding and that it is impossible to obtain good quality joints because of oxides and other foreign additives in the butt.

CHAPTER I

THE FEATURES OF FRICTION WELDING

All known welding methods are usually divided into two large groups: fusion welding and pressure welding (or plastic deformation welding).

In fusion welding the edges of the parts being joined are melted and the gap between them is filled with molten metal. The formation of the permanent joint takes place as a result of cooling and crystallization of the metal of parts being joined and the filler metal (in cases when filler metal is used).

The pressure welding takes place, as a rule, in the solid phase, without the melting of metal. The permanent joint is formed as a result of bringing close the joining surfaces to such small distances (commensurate with interatomic) at which, during known conditions, strong bonds are developed between connected points. These bonds are analogous to forces of interaction of atoms in one-piece metal. Each single bond is insignificant in magnitude. The welding joint can be obtained only in the case when the number of such bonds (interacting points) is extremely large. One of the necessary (however, not sufficient) conditions during this process is the high plasticity of the metal at connected surfaces of the parts being welded.

Some metals, for instance copper, aluminum, lead, silver (which are sufficiently plastic under normal conditions), are pressure welded in room and even in negative temperatures.

Such a process of joining plastic metals is called cold welding. Other metals must be subjected to artificial increase in plasticity by heating the joining surfaces to relatively high

temperatures which, however, are not higher than the temperatures of melting points for welding in solid phase.

Pressure welding includes forge, gas pressure, electric resistance, and other types of weldings.

Friction welding is also a type of pressure welding. The welding joint is formed as a result of joint plastic deformation of parts being joined in the solid phase. It differs from other types of pressure welding first of all by the heating method, more precise by the introduction of heat into the welding joints. During friction welding, the mechanical energy is directly converted to the thermal energy. The generation of heat is strictly localized in thin surface layers of the metal. It is shown below that this feature of the process predetermines the basic advantages of friction welding.

The simplest scheme of the friction welding process is pictured in Fig. 1. Two parts, subject to welding, are placed coaxially in the machine clamps. One of them is stationary, the other rotates around their common axis. At connected surfaces of the parts, which are pressed against each other by the axial force P, friction forces are created. The work expended during the relative rotation of the parts to overcome the axial forces is converted into heat, which is liberated at the friction surfaces. This causes the surfaces to be heated to temperatures necessary to obtain welding joints (in the case of welding of ferrous metals these temperatures, depending on the process regime, are in the 950-1300 degrees C range. Upon achieving the required

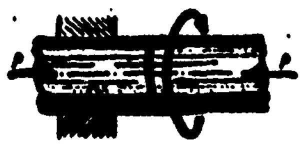

Fig. 1. The basic scheme of the friction process

temperature, the relative motion of the surfaces should be (if possible) stopped rapidly (practically instantaneously). The heat liberation will also stop. The formation of the welded joint is achieved by "peening": to the heated but stationary parts clamping force is applied for a certain period. During and after the peening, natural cooling of the welded parts takes place.

The friction welding has a series of important virtues, many of which are a result of the localization of the heat liberation in the thin surface layers of the metal, i.e., where it is required for welding purposes.

High productivity. The volume of the thin layer of the heated metal is so insignificant that the entire heating cycle takes a small time interval -- several seconds to 1/2 minute (depending on the properties of the material and the size of the cross section of the parts being welded). Therefore, the productivity of the friction welding is very high. In this respect, only electrical resistance welding can compete with it.

Small consumption of energy and power. The small volume of metal heated during friction welding predetermines the extremely good characteristics of the process. The consumption of energy and power (Fig. 2) for friction welding is 5-10 times lower than for resistance welding.

Usually the main power for friction welding machines is the asynchronous motor. Therefore, the power required for welding is uniformly distributed between three phases of the electric power supply line with a high (motor) power coefficient $\cos \phi$ = 0.8 to 0.85 (in electrical welding, the line load, as a rule, is one phase with significantly lower power coefficient).

High quality of the welded joint. One of the more important advantages of friction welding is the high quality of joints obtained. When the welding regime is selected correctly, the butt metal and the adjacent zone have a strength and plasticity which are not lower than the strength and plasticity of the base metal of the welded parts. This is explained as follows:

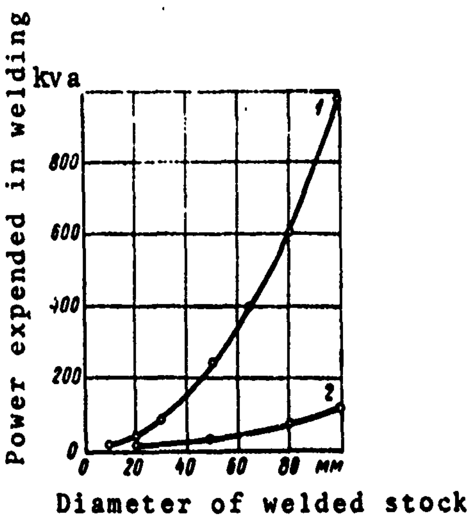

Fig. 2. Required line power:
1 - for electric resistance welding.
2 - for friction welding.

1. All oxide and adsorbed films and various foreign particles, which always cover metallic surfaces and prevent the formation of the welded joint, are removed from the butt into the flash during friction welding because of the mechanical wear of the connected surfaces during friction and deformation of the metal in radial direction. As a result of this, the characteristic "collar" is formed (Fig. 3). The tight contact between the friction surfaces prevents new formation of oxides during the welding process. As a result, there are no poor penetration, pores, cavities, oxide and slag additives, cracks, and other macro-defects;

2. In the butt and in the adjacent zone of thermal effect, the metal achieves a structure with equiaxial and sharply refined (as compared with the base metal) grain. Such structure is formed as a result of rapid local heating of small metal

volumes and high rates of their cooling (intensive heat removal into the surrounding metal) under significant pressure of 300 - 500 atm and higher.[1] Besides, mechanical refinement of grains occurs during the friction process.

The thin structure of the metal, free from macro-defects, determines the good mechanical indicators of the welded joint.

Besides the advantages mentioned above, the friction welding has others not less important.

<u>The stability of quality of the welded joints</u>. A party of pieces produced with the help of friction welding without re-adjustment of the machine has constant quality of the joints and according to a series of indicators (temporary resistance to fracture, angle of bending, viscosity) the difference in the magnitude of the angular force and the heating period. In addition, it is explained by the fact that the properties of the welded joint do not depend on such external (disturbing) factors as oscillation in the voltage of the power line, the quality of auxiliary materials, the qualification and the physical condition of the welder. These factors have an effect on the stability of properties of the welded joints in other types of welding.

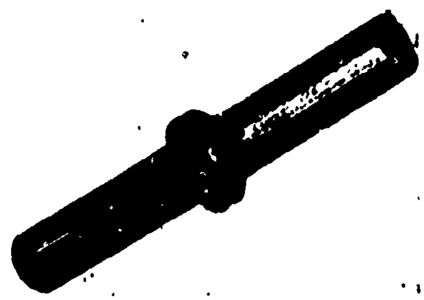

Fig. 3. Steel rods welded by friction with burrs formed on them.

The high stability of the mechanical indicators of the welded joint, which is a very important feature of the friction welding process, makes it possible to use selective inspec-

tion of products, for instance, by destruction of several parts selected from a certain batch. Especially, this is important under present production conditions where there is practically no simple, cheap and reliable methods of non-destructive inspection of welded butt joints suitable for use in the welding or preparing shops.

Fig. 4. Friction welding of low carbon steel. Structure of the butt metal (a) and of the base metal (b)

The possibility of welding metals and alloys in various combinations. The extensive industrial experience in application of friction welding accumulated already shows that one of the most important advantages of friction welding is the possibility of strong joints between not only similar metals but also between large number of combinations of different metals and alloys, including such, whose thermophysical characteristics are sharply different. With the help of friction welding joining of metal parts was accomplished and introduced into the industry, which is not possible with other types of welding or are obtained with considerable difficulty, for instance aluminum with steels, titanium with aluminum, copper with steel, and others.

The possibility of welding of parts with unprocessed surfaces. Friction welding is favorable in relation to contamination and purity of processing of surfaces of parts intended for welding. In this respect, it differs positively from the electrical resistance welding where a careful cleaning of the surfaces is necessary, which consumes a lot of time. Surfaces intended for joining, in a majority of cases and especially during welding of parts from similar metal, do not require purity and precision of processing. Contamination and rust is permitted. A non-perpendicularity of rotation axis ends is allowed between 5-7 degrees without noticeable decrease in the quality of joint. Slag is not allowed at the friction surfaces. Its presence can lead to formation of bad quality joints.

Hygiene of the process. Friction welding differs favorably from other types of welding in the hygienity of the process: the absence of ultra-violet radiation, harmful gas emission, hot metal spatter, and others. This made it possible for many enterprises to install machines for friction welding in the mechanical processing line of parts. This, in turn, made the transportation of parts from mechanical processing shops into welding shops (and in reverse) completely unnecessary. As a result, savings were possible.

The simplicity of mechanization and automation. The basic parameters of the friction welding process are easily programmed. As a rule, all equipment for friction welding is either semiautomatic with minimum use of manual labor or automatic whose operation is without the participation of man.

The high degree of mechanization and automation of the friction welding equipment combined with hygienity of the process substantially alleviates the labor process compared

with other, traditional types of welding.

A very substantial feature of friction welding is the limit of the use of this joining method regarding shape and size of the welded parts.

During rotational motion, the friction welding makes it possible to obtain good results only in those cases when one of the parts intended for welding is the body of revolution (rod or pipe), whose axis coincides with the axis of rotation, and the other part has a flat surface with which the end of the first part is in contact. This feature of the process leads to following possible joints of friction welding: rods butt to butt, pipes butt to butt, rod butt to butt with pipe, T-shape joining of rode or pipe with flat surface parts. In the last case, the shape of the part with flat surface and its size is immaterial from the point of view of the welding technology. The size and the shape affect only the selection of the clamp design for clamping the part in the welding machine (Fig. 5).

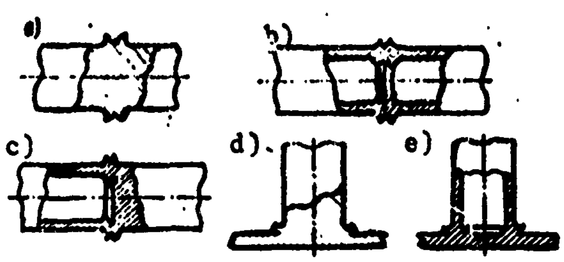

Fig. 5. Types of welded joints done by friction welding: a-rods butt to butt; b-pipes butt to butt; c-rod and pipe butt to butt; d and e-T-shape joints of rod and pipe with flat surface part.

The possibility of application of friction welding, up

to now, is limited not only by the shape but also by the size of the cross-section of the welding parts at the place of their contact. Calculations show that to use this process for welding of rods with continuous cross section with a diameter of more than 200 mm is hardly expedient at the present state of the art. In reality, to weld such rods (cross section more than 30,000 sq. mm) a machine would be required with the motor power in the order of 500 KW, a revolution rate of 100-150 r/min and an axial force of more than 300 tons.[2] The equipping of such a machine and its operation would be so costly that it would hardly be profitable despite the high productivity of the friction welding process. In such cases, it is more expedient to use, for instance, the electro-slag welding, where using simpler equipment with significantly lower cost one can produce joints in parts with large cross sections, although it takes longer.

Concerning the lower limit of the diameter of parts joined by friction welding, it should be noted that it was impossible to join rods with a diameter of less than 3.5 mm even under laboratory conditions. Special equipment with the rate of revolution of the axis in order of 100,000 RPM and with a complicated device for instant braking of the axis is required for such small parts. Besides, when welding thin rods additional difficulties arise connected with their instability in longitudinal bending and with increased requirements for co-axial installation in the machine. As far as is known, rods with less than 6 mm diameter were not welded under production conditions up to now.

Calculations and practical experience in friction welding, as well as consideration of industrial requirements, lead to the conclusion that the range of cross sections that can be friction welded at present lies between 30 and 8000 sq. mm. These numbers refer equally to rods and pipes. There is no

doubt that as the friction welding technology and equipment is improved, this range will be widened. In a British delegation report at the Friction Welding Colloquium (XXI Assembly of International Welding Institute, Warsaw 1968) it was stated that a unique miniature machine for friction welding of wires and tubes with outside diameters of 0.75 and 1.55 mm and revolution rates corresponding to 38,000 and 20,000 RPM was designed in Great Britain.

The indicated limitations of friction welding, connected with shape and size of the cross section of welded parts, do not diminish the rate nor the volume at which the friction welding is being adopted. An analysis of production of machine building industry and some other branches of Soviet industry indicates that the majority of welded parts (up to 50 and 70%) have annular cross sections. The size of the cross sections doesn't exceed the recommended limits above.

A serious factor which retarded for a long time the application of friction welding was the absence of centralized production of the necessary equipment. Despite the apparent advantages of this type of welding, many enterprises refused to adopt it because they had to produce the equipment themselves. Only a few plants used the documentation for friction welding equipment worked out by the ASRIEWE, made their own creative contribution, and with success introduced this progressive method of welding. Despite the fact that such manner of equipment production is by far not the most economical, the pioneers in the friction welding application (Minsk Tractor Plant, Gor'kiy Automobile Plant, Chelyabinsk and Altay Tractor Plants) rapidly enjoyed significant savings when they adopted this path. The experience of these and, now, many other plants showed that friction welding can compete successfully with other, traditional types of welding. It proved to be that

friction welding can be used most efficiently in production of cutting tools; in production of composite forged, casting, or stamped parts; and also in cases when a one-piece part is replaced by a welded bi-metallic part because of economy of an expensive or rare material. The friction welding in a series of cases could not be replaced by another type of welding in joining of different materials which were hard or impossible to weld before such as aluminum-steel, austenite steel-perlite steel, and many other exotic compositions.

In all enumerated cases, the economic efficiency was not to be disputed. The expensive equipment paid for itself after 4-6 months of two shift operation. On the average, each friction welding machine pays for itself in one year.

The industrial application of friction welding began to develop rapidly since the Volkovysk Plant of Casting Equipment began to mass produce general friciton welding equipment in 1965. Somewhat later the Moscow plant "Frezer" began to produce special friction machines for cutting tool products.

In recent times, studies were performed which will make it possible to enlarge the application of friction welding and also to use the friction heat in other areas of metal processing. Thus, a new scheme for the welding process is proposed (14). This scheme uses an auxiliary part (third body), which rotates and is clamped between two non-rotating parts to be welded (Fig. 6a). Whis will allow the welding of large parts where the rotation and the rapid braking at the end of the process is very difficult or impossible. This welding scheme makes it also possible to weld two (outer) parts if, after welding, they have to be mutually oriented in a certain manner.

In Fig. 6b the vibro-friction welding scheme is presented. The distinguishing feature of this scheme is the contact of

one of the parts being welded by rapidly changing reciprocal motion in the friction plane with relatively small amplitudes. The elimination of the rotational motion in this case makes it possible to friction weld such parts, whose cross section may not only be annular but have any other shape.

Together with friction welding, the building-up by friction is being developed. It is proposed to use the friction heat also for forming metallic pieces and for other cases.

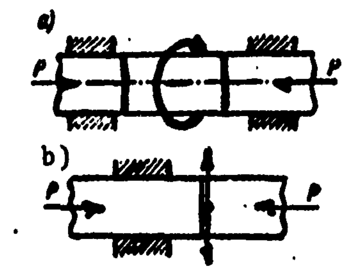

Fig. 6. Possible schemes of friction welding: a - welding of two stationary pieces by rotating a third between them, b - vibro-friction welding (Relative reciprocating motion in the plane of the butt with relatively small amplitude at sonic frequency.

Thus, in a comparatively short time, friction welding is applied broadly. The interest in this progressive and very economical type of welding and other processes using friction heat is constantly growing.

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1. The pressure during heating is usually 3-5 kg/ sq. mm.

2. The data given in this example refer to the welding of low carbon steel.

CHAPTER II

MECHANISM OF FORMATION OF A WELDED JOINT IN SOLID PHASE

Despite the apparent simplicity of the process, the mechanism of formation of welded joints in solid phase (plastic deformation) is really quite complicated. For many years the nature of the formation of strong bonds between two, previously separated surfaces was the subject of intent study of theoreticians and experimentalists, a cause of long discussions. Even at present time, there are no clear answers.

A series of hypotheses was put forward, which with different degree of reliability describe the process and the mechanism of formations of joints in the solid phase. For instance:

film hypothesis (3): The authors of this hypothesis assume that to create interaction forces between the surfaces of two bodies it is necessary to clean these surfaces from oxide, absorbed grease and gas films and that the joining of clean surfaces takes place as a result of flow of metal surface layers with plastic deformation of joining bodies.

recrystallization hypothesis (28,77): This hypothesis is based on understanding of the recrystallization as the basic factor which determines the joint formation in solid phase. According to this hypothesis, the deformatior and accompanying cold hardening of the metal, with simultaneous action of relatively high temperatures, lead to restructuring of atoms in crystal lattices of the joining bodies and to formation at the boundaries of these bodies of new grains, which belong to both bodies at the same time.

diffusion hypothesis (38): According to this hypothesis,

the basis for formation of bonds between surfaces in contact are processes of mutual diffusion transfer of atoms deep into the joining bodies;

<u>energy hypothesis</u> (46): The basis of this hypothesis is the notion of necessity of activization of atoms in surface layers of metal of joining bodies by additional outside energy. (in heat, mechanical or other form). The magnitude of this energy should be higher than some critical level, which is completely determined for each metal.

All mentioned hypotheses treat the formation of the joint in solid phase from different scientific positions. However, up to now, not one of them revealed this phenomenon in all its diverse manifestations. In recent times, some basic ideas on basic features of the joining process were put together.

The majority of researchers insist that the joining of metals in solid phase is due to appearance between the contact surfaces of so-called "metallic bonds", i.e., the interaction of the same forces between atoms (ions) of two neighboring bodies in contact, which always takes place inside one-piece metal and determines its continuity. The contemporary physics (§4) considers any metal as a combination of positively charged ions (located, in the ideal case, in the crystal lattice points and a large number of free electrons, which are in constant interaction simultaneously with many ions in the metal volume considered. This interaction of a "cloud" of collective electrons with ions of the points determines the continuity of the metal.

Under known conditions, such forces can arise between the surfaces of two joining metal bodies. During their approach

to very small distance commensurate with the parameters of the crystal points (several angstroms), the bodies begin to exchange their free electrons which move through the surface of the partition. As a result of such exchange, a common cloud of collective electrons is formed, which interacts simultaneously with ions belonging to both bodies in contact. Metal bonds are formed between the surfaces in contact (previously separated).

The magnitude F of such interaction forces, according to Schaller is inversely proportional to the distance r between the interacting points of the surfaces.

$$F = \frac{a}{r} \qquad (1)$$

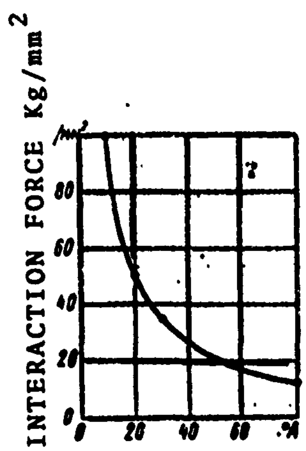

Fig. 7. The relationship between the interaction force and the distance between the interacting points of the surface.

The graph of this relation- is shown in Fig. 7.

Such a point of view makes it possible to assume that during approach of ideally smooth, pure and parallel surfaces metal bonds could arise between them spontaneously, without external energy consumption. These bonds are sufficient for formation of joints, which are of the same strength as one-piece metal.

However, ideal surfaces do not exist. Real metal surfaces are always covered by films of oxides and absorbed greases and gases, which inhibit the formation of metal bonds. In addition, the surfaces are never smooth.

The surface of any, even carefully polished, solid body is uneven, rough, and covered with microscopic irregularities. (Fig. 8). When such surfaces approach each other, their initial contact takes place only at separate points at the crests of the undulation. The contact, therefore, has a discontinuous character (discrete character). Usually, one must distinguish: a. nominal (geometric) contact area S_n determined by external boundaries of the contacting surfaces; b. contour contact area S_k representing the total surface of the crests containing the area making physical contacts (microprojections) with each other. A volumetric crumpling of the projections in contact is produced when a load is applied to the contact surfaces. Here the contact has mixed elastoplastic character; c. the physical (actual) areas of contact ΣS_f representing the total of the small areas in actual physical contact with microprojections.

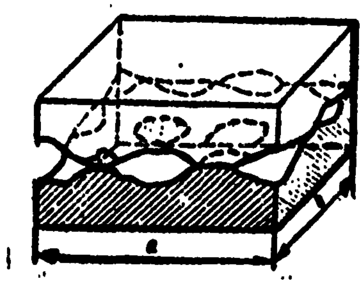

Fig. 8. A model of uneven and rough surface. The dots represent the areas of physical (actual) contact; the contour area is outlined by dotted lines; the nominal area S_n = ab (33).

The size of the surface of contact of each such microprojection free from load depends on the properties of the material, the purity of the surface processing, and a series of other factors and can have an area from a fraction of a square micron to several thousands of square microns.

Despite the fact that the number of microprojections in

simultaneous contact can be very significant, the actual contact area of surfaces in contact ΣS_f is several times less than the nominal area of contact S_n and is from 1/100,000 S_n to 1/100 S_n. It is clear, given such sizes of the total actual area of contact that the strength of such joint as a whole will be much lower than the strength of the original material of the piece, even if interaction forces are created between the contacting bodies, which are due to metallic bonds, i.e., if first sources of "seizing" of surfaces will appear and if the local strength of these sources is very high. Therefore, during formation of separate sources (connections) of seizing even if their number is relatively large, one cannot talk about a welded joint. The terms "seizing" and "welding" cannot be identified because of the difference in units. The single seizing should be considered as an elementary process, which is the basis of the welded joint formation. But the welded joint can be obtained only if the single seizings spread along the entire nominal area or, at least, along a large part of it. Using mathematical terminology, this thought can be expressed as follows: the welding is the integral of seizing along the nominal surface of the contact.

Thus, the welding of two bodies in solid phase is possible when two conditions are observed:

obligatory purification of the joining surfaces from substances adsorbed by them and from oxide films and the assurance of a contact between pure surfaces;

maximum increase in the area of actual contact of joining surfaces (in the limit - up to nominal contact area).

The first of the mentioned conditions in friction welding can be fulfilled (see chapter V) with comparative ease because

of the wear of the surfaces.

The second can be met by compression of the bodies by external forces. When this is done, only a small number of microprojections will be in contact at the first moment. This is because all microprojections covering the surfaces have different heights. Under the action of the external force large stresses are produced in these microprojections, whose actual area of contact is negligibly small. Their calculated values are significantly higher than the yield point. The microprojections under load will be instantly crumpled. The surfaces will come closer by the magnitude of crumpling deformation. New microprojections will be in contact. The surfaces will continue to come closer and a larger number of microprojections will be in contact. The total actual area of the surface contact will progressively grow as a result of increase in the number of interacting microprojections, as well as because of the growth in contact areas of each microprojection.[1]

The above discussion leads to an extraordinary conclusion: the formation of strong joints in the solid phase is not possible without joint plastic deformation of micro-volumes of metal surface layers of joining bodies.

To insure plastic deformation it is necessary to apply external forces to the joining bodies and to expend some work.

The degree of plastic deformation (shown measure in this case may be the magnitude of the total actual area of contact ΣS_f), the condition of the metal at surfaces and joining pieces σ_τ, and the force P necessary to insure deformation are governed by the following approximate relationship:

$$P \approx \sigma_\tau \Sigma S_f \qquad (2)$$

It was shown experimentally, however, that for welding of actual pieces the crumpling of microroughness at their surfaces alone is not sufficient, because oxides and various adsorbents are not removed from the butt and inhibit the formation of metal bonds. To remove films of these substances one has to insure the plastic flow of micro-volumes of the metal in the plane of the butt. To achieve this, additional external work is required. Then, the magnitude of force compressing the pieces becomes larger than the calculated magnitude obtained from equation (2).

By lowering artificially the yield point σ_T, one can significantly improve the plastic deformation of the metal of joining pieces and thus alleviate the welding problem.

In the majority of metals, the value of the yield point is lowered with increase in temperature. This property was long used, for instance, in forge welding when pieces to be joined were pre-heated and then were subject to compression by hammer blows. Essentially, the same process takes place in the contemporary gas pressure welding: the pieces are heated to high temperatures, which do not reach the melting point, then they are compressed by applying external static force. Analogous process takes place during electric resistance butt welding: the pieces are heated by Joule heat and compressed at the same time. The same general principle of welding joint formation in the solid phase, namely heat-pressure, is the basis of friction welding.

Thus, in almost all known types of pressure welding, the heating is used as means of promoting the achievement of the welded joint in solid phase. All types of pressure welding are distinguished from each other by the method of heating (the method of introduction of heat into welding pieces) and by

the method of application of the external compression force.[2]

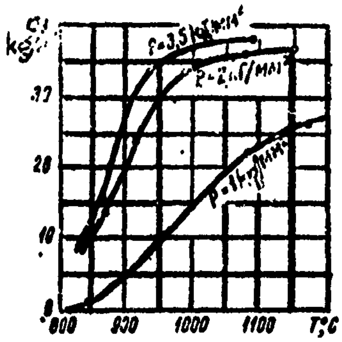

Fig. 9. Dependance of the strength of the welded joint on temperature and pressure during welding.

The dependance of the welded joint strength, completed in solid phase, on temperature and magnitude of the external force confirms well Esser's studies whose results are presented Fig. 9. It is apparent that at constant temperature (constant yield point) the strength of the joint grows as the external compression force is increased (increase in the total actual contact area) and that during constant external compression force the strength grows as the temperature is increased, i.e., the yield point decreases.

Studies of recent years made the discussion presented above on pressure welding mechanism possible.

M. KH. Shorshorov and others (56,57) created a new hypothesis as a result of an analysis of theoretical works and experimental data. This hypothesis does not contradict the above discussed views and does not reject earlier hypotheses. It explains in significant detail the phenomenon of joining in the solid phase and in a number of cases it permits even mathematical interpretation. This new hypothesis considers the process of formation of welded joints in solid phase as consisting of two stages, which are consecutive in time:

A. The formation and development of the physical contact

between surfaces. As a result of crumpling of microprojections the number of single contacts (seizing connections) between the surfaces grows and the total area of the physical contact ΣS_f increases, tending to its limit - the nominal area S_n;

B. The appearance between the surfaces of strong bonds of chemical nature.

The authors present the kinetics of this process as it is presented in Fig. 10.

Stage A - the maximum approach of surfaces and cleaning of these surfaces from oxides and adsorbed films is characteristic of primary formation of the physical contact.

Stage B - the primary formation of chemical bonds which specify the strength of the joint is characteristic of stage B. In both stages the plastic deformation of metal plays the main role. Because of the creep in stage A the approach of the surfaces and the increase in the area of physical contact take place. Because of creep and microdeformation of the surface layers of the metal in stage B the chemical activation of metal is provoked (formation of seizing connections).

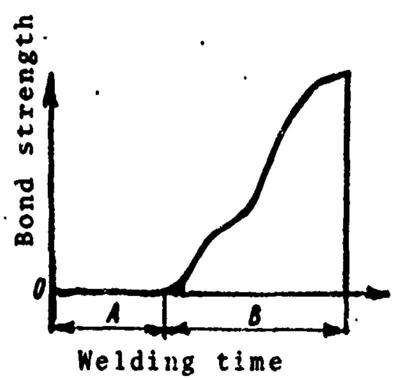

Fig. 10. The process kinetics for formation of joints in solid phase: A - the stage of formation of physical contact between the surfaces; B - the stage of initiation of chemical interaction (56,57).

Considering the microprojections of contacting surfaces as spherical or conical formations or as elements of other form and using the laws of the theory of creep, the authors of the hypothesis obtained the following relationship for the period of the discussed stages t. These equations agree satisfactorily with experimental data (57):

for stage A

$$t_A = A\frac{1}{Bp^m} \exp\left(\frac{E}{kT}\right), \qquad (3)$$

where p - average pressure at the surface of an ideally smooth worked surface (the practical purity of the treatment is taken into account by coefficient A)

B - coefficient

T - temperature (absolute)

k - constant

m - stage index (usually m = 4 to 5)

E - energy of creep activation

for stage B

$$t_B = \frac{1}{v(p;c)} \cdot \frac{N}{N_o} \exp\left(\frac{Ea}{kT}\right) \qquad (4)$$

where v - frequency of atom oscillations or frequency of vacancy transfer

c - coefficient characterizing the properties of the material

$\frac{N}{N_o}$ - 0.7 to 0.9 proportion of the required number N of broken bonds to the number of bonds N_o per unit of surface

E_a - energy of a single bond, energy of activation of dislocation motion and energy of activation of formation and vacancy transfer.

The authors note that the division of the process into two demarcation stages is somewhat conditional. In actuality, the chemical phenomena arise already in the first stage and the formation of the physical contact may be finishing in the second stage. However, the predominance of the physical and chemical roles correspond to the particular stage of the phenomenon.

Further, the authors note that the demarcation of stages is especially sharply expressed during the joining of different materials. At the same time, in the joining of similar materials the stages of physical preparation of contact and the cnemical activation of joining surfaces usually coincide in time and in this case the separation of the process into two stages has only formal significance, which allows better understanding of its laws.

However, when joining the materials with various degree of plasticity, the division of the process into two stages completely corresponds to the reality. The tight physical contact in this case is formed as a result of easy and rapidly processing deformation of the more plastic metal. The strong joints occur after a certain time. Because of the more difficult deformation and slowed down rate of the emergence of dislocations to the surface in the harder metal of the given pair the number of active nodes in the beginning is insufficient and additional time is required to achieve the optimum number of active nodes. The result of this phenomenon may be observed, for instance, during friction welding of aluminum with steel and some other different metals and alloys.

1. The notion on the growth of areas of single contacts during the process of bringing together of two surfaces under the action of external forces is not shared by several scientists.

2. Only some metals, having low limit of plasticity at normal temperatures, - copper, aluminum, silver, lead, and some others - can be pressure welded without heat with the help of the so-called cold welding.

CHAPTER III

BASIC INFORMATION FROM THE FRICTION THEORY

In the preceding chapter contemporary ideas on the joining process in solid phase were considered shortly.

This process, apparently is complicated and varied. Friction welding, one of the variants of pressure welding, is more complicated because, besides encompassing all features of the solid phase welding process, it also is based on laws of friction processes. It combines such phenomena as heat liberation and wear of surfaces in friction; continuous formation and immediate destruction of bonds between contacting surfaces during their continuous relative motion; almost instant heating and rapid cooling of small volumes of metal under significant pressures; elastic-plastic deformation in micro-volumes of rough surface projections and in micro-volumes of metal layers adjacent to these surfaces; cold hardening and recrystallization of metal; mutual diffusion and also introduction of microscopic particles of metal from one of the pieces being welded into the body of the other, etc.

Almost all processes named are subjects of study in the contemporary friction science. The development of this science is connected with the necessity of improving friction machines and mechanisms. Among the practical problems, which are solved by the friction science are the following: maximum reduction of heat liberation at friction points, creation of conditions which will prevent jamming or seizing of the friction surfaces, and similar problems. Apparently, these problems are directly opposite to tasks set during the study of friction welding. Besides, the range of conditions studied so far by the

friction science only borders, but does not coincide with the range of conditions which are utilized during friction welding. Nevertheless, the consideration of the friction welding process should be based on the continuously developing contemporary friction science. Sufficiently extensive literature already exists in this field.

1. Basic Ideas of the Contemporary Friction Theory[1]

Exterior friction (or simply friction) is the resistance created between two bodies in contact with each other under the application of a compressive force during their relative motion in the plane of contact. The resistance force (acting in a direction opposite to the force of motion) is called the friction force.

The ratio of the friction force to the compressive force between the two bodies (normal to the plane of contact) is called the friction coefficient.

From a kinetic standpoint there are three types of friction:

1. sliding friction, where the same nominal surface of one body is moved forward on the surface of another body;

2. rotational friction, where the surface points of one body, located in a contact plane of two bodies, describe concentric circles around the center located on the rotational axis. Rotationl friction is a special case of sliding friction.

3. rolling friction.

The following types are distinguished on the basis of fric-

tion surface condition and the lubriction:

1. pure friction, created on surfaces without adsorbed and oxidized films. Such surfaces are formed, in particular, under considerable plastic deformation when brittle films are destroyed, exposing pure metal. Pure friction is accompanied by "jamming" ("seizing"), forming of points of engagement between the surfaces performing the work;

2. dry friction, created without lubrication and contamination of the surfaces;

3. marginal friction, when the friction surfaces are separated by a lubricating film of insignificant thickness (0.1 micron and less), having special properties different from the volumetric properties of the lubricant, which depend only upon the nature and condition of the working surfaces. The marginal film has a stratified structure; the molecules of the lubricant are connected to the metal by its active ends creating interference. At sufficiently high temperatures (about 200 degree C) the orientation of the molecule layers is disturbed and some chemically active lubricants react with the metal;

4. fluid friction, where the surfaces are completely separated by a layer of fluid.

One can distinguish intermediate friction types - semi-dry and semi-fluid friction.

Depending upon the working conditions of the friction surfaces, the wear of the friction surfaces can be of different nature. The following types of wear are distinguished: a. abrasive wear, b. wear due to plastic deformation, c. wear

during brittle failure, d. wear during seizure (molecular-mechanical), e. corrosion wear, f. oxidation wear.

During friction welding there occurs primarily one of the above-named types of wear — molecular-mechanical wear during seizure. It is characterized by the fact that between the metal particles belonging to two different bodies whose adjacent surfaces are shifted relative to one another, there may occur such stable bonds that their destruction during continued motion of the surfaces occurs not along the previous boundary of the bodies but as a result of the removal of one of the particles from the body to which it belonged prior to this time. The dimensions of the detached particle and the remaining depression are different, and depend on the friction regime. By changing the velocity of the relative motion of the surfaces and their compression forces, the wear processes can be reduced to polishing (smoothing) of the surfaces; here the strength of the forming joint also changes. Under other conditions, friction welding can also be accompanied by wear due to plastic deformation.

2. Friction Force and its Nature

In connection with the discontinuity (discreteness) of the contact between two adjacent real surfaces, friction force is examined as the resultant of the elemental forces arising during the interaction of many pairs of projections. These elemental forces are small, but the friction force can reach relatively high values, since on the nominal contact surface there may be a rather large number of simultaneously interacting projections.

Until recently there have existed two hypotheses on

the nature of the interacting forces between the elementary surfaces at the point of actual contact and, consequently, concerning the nature of the friction phenomenon itself (31).

1. The mechanical hypothesis. This hypothesis arose during the period of turbulent development of mechanics and explains the friction phenomenon on the basis of a purely mechanical interlocking of projections of the two contiguous surfaces I and II (Fig. 11). The interlocked projections resist relative displacement as a result of the application of an external force. They are either bent like elastic beams possessing one end fixed into an elastic support or they are worn down by each other. In either case, the reaction of each projection is considered an elementary friction force.

2. The molecular hypothesis. This is a more recent hypothesis and explains friction as resulting from a molecular interaction of two surfaces brought so close together that actions of molecular forces become noticeable. This condition can be satisfied only by the individual projections. Therefore, the molecular field over the entire rough surface is of intermittent nature, as a result of which a certain force, equal to the friction force and opposite in sign, must be applied to overcome it and to produce a tangential displacement.

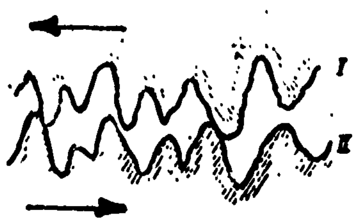

Fig. 11. Model of friction surfaces (33)

A full explanation of all friction phenomena, however, cannot be given by applying these hypotheses.

To overcome this deficiency, I.V. Kragel'skiy developed (31) a

unified molecular-mechanical friction theory. According to this theory, friction has a dual nature and is the result of mechanical as well as molecular interaction of surfaces, where, depending on the conditions under which friction takes place, the mechanical or the molecular interaction predominates.

In light of the present knowledge of science of friction, Amonton's law[2] $F = fP$ (where F - friction force, f - coefficient of sliding friction, P - normal pressure force) has been modified.

In accordance with Amonton (1663-1705), the friction force is a funtion of the applied normal pressure only, and the friction coefficient is a constant. However, Coulomb (1736-1806), established (34) that the friction coefficient is reduced with an increase in the normal pressure force. Coulomb also noted the dependence of the friction coefficient upon the sliding speed.

On the basis of the unified molecular-mechanical friction theory, the following relationship has been established, which is called the general law of dry and marginal friction:

$$F = S_f\alpha + \beta P \qquad (6)$$

where F - friction force

S_f - sum of the actual areas of elementary contacts

α, β - constant coefficients characterizing the material of the friction surfaces

P - normal pressure force.

Determining as before the friction coefficient as a

ratio of the friction force to the normal pressure force, one can obtain by rearranging equation (6) the following expression for the friction coefficient:

$$f = \frac{F}{p} = \alpha \frac{S_f}{p} + \beta \qquad (7)$$

It can be seen from equation (7) that in the general case, for a given pair of materials the friction coefficient is not constant, but depends upon the normal pressure; the first term of the right part of the above equation is a correction of Amonton's law.

In certain special cases, however, the friction coefficient does not depend upon the pressure, e.g.,

a. for a pure plastic contact when the relationship

$$\frac{p}{S_f} = \sigma_T = \text{const.}$$

exists, where σ_T yield point, then

$$f = \frac{\alpha}{\sigma_T} + \beta = \text{const.}$$

b. for high values of actual unit pressures

$$\frac{p}{S_f}$$

when the first term of equation (7) becomes small and its variation as a result of a change in the normal pressure becomes a small number of the second order, so that for practical purposes one can say that the following formula

$$f = \alpha\frac{S_f}{p} + \beta \approx \beta = \text{const.} \qquad (9)$$

also applies in this case.

3. Variations of the Coefficient of Sliding Friction

Contrary to the originally established assertions about the constancy of the friction coefficient, contemporary research has proved that it actually does not stay constant. It varies not only with a change in normal pressure, but also as a function of a number of other factors. For example, in the sliding friction of steel on steel, the friction coefficient might vary, as experience has shown, over a very wide range (from 0.1 to 1 and higher), depending on the conditions prevailing during the friction process, and all this may be with the accordance with natural laws, since dry friction is a complex physical phenomenon which depends upon many factors, and in which the mechanical destruction of the material is combined with the interaction of molecular fields. It is understandable that under such conditions one cannot describe the friction by one parameter constant for a given pair of materials - the friction coefficient.

I.V. Kragel'skiy and I.E. Vinogradova (33) indicate that at least the following 9 factors have an influence on the friction coefficient:

1. the nature of the material and the presence of films on the friction surface (lubrication, oxidation, contamination)
2. the duration of contact without movement
3. the speed of application of the load
4. the rigidity and elasticity of the friction surfaces
5. the relative speed of motion of the friction surfaces
6. the temperature of the friction surfaces
7. the magnitude of the normal pressure force

8. the charcter of the contact between the bodies, area of the contact surface, coefficient of overlapping

9. finish of the surface and roughness.

Of the above factors, the following seem to be applicable to friction welding:

1. the relative speed of motion of the friction surfaces
2. the temperature of the friction surfaces
3. the nature of the material and presence of surface films
4. the magnitude of the normal pressure force
5. the rigidity and elasticity of the friction surfaces

At the present time, there are no comprehensive data available that reflects the combined influence of these factors on the friction process; however, there are some data that are applicable to friction welding that may be quite useful.

Influence of the relative speed on the friction coefficient. As a result of numerous experiments concerning this relationship, several points of view (34) have become established. Some scientists feel that the friction coefficient increases with speed; others cite generalized conditions derived from experiments in the form of equations that indicate that the friction coefficient decreases with speed; and, finally, there are investigations that prove the independence of the friction coefficient from the speed of sliding. Such contradictions cannot be explained by errors, since most of the experiments were conducted with great accuracy. One has to suppose that the results of the experiments were influenced by the conditions under which they were carried out, i.e., one cannot investigate the influence of the speed of sliding alone, without at the same time taking into account the influence of

other parameters on the friction coefficient. This is confirmed when reviewing (33) the most general equation for determination of the friction coefficient.

$$f = (a + bv)\, e^{-cv} + d, \qquad (10)$$

It can be seen from this equation that with an increase in the speed (v) the friction coefficient either increases steadily or decreases steadily, or passes a maximum, or finally stays constant, all depending on the numerical relationship of the coefficients a, b, c, and d entering into this equation.[3] The values of these coefficients depend on the properties of the bodies, the unit pressures, the hardness of each of the bodies, and other factors, and they must be determined for a given pair of materials under actual working conditions. It is known, however, that the position of the curve maximum (Fig. 12) is a function of the magnitude of the unit pressure and the hardness of each of the materials. The higher the unit pressure and the greater the hardness of the material, the lower the speed to which the curve maximum corresponds.

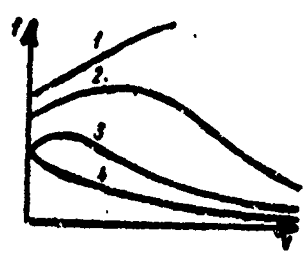

Fig. 12. Dependence of the friction coefficient upon the speed of sliding for various unit pressures (33): 1 - small unit pressure, 2 and 3 - average unit pressure, 4 - considerable unit pressure.

A major deficiency of equation (10) is that the friction coefficient is determined only as a function of speed, without taking into account other parameters of the friction process, such as the pressure. Evidently, future research faces the task of discovering the complex laws of the dependence of the friction coefficient upon the speed of sliding, unit pressure and other factors. Testing of friction welding is faced with a similar program. Besides the magnitude of normal pressure, the speed of relative motion and the properties of materials interacting during friction of surfaces, the condition of these surfaces has a large effect on the friction coefficient. It is established that the friction coefficient of the same pair changes to a significant degree depending on the purity of the surface. During interaction of poorly processed surfaces an increase in the friction coefficient is observed when compared with the values corresponding to pure processing because the higher microprojections insure better linking of the surfaces and, consequently, high friction force.

During friction of very smooth surfaces a higher friction coefficient is also observed. This is due to increase in forces of the molecular interaction between these surfaces.

A signigicant effect on the friction process is due to the degree of contamination of the interacting surfaces. Films of various kinds of lubricants, adsorbed by these surfaces, contribute to the lowering in the friction coefficient and in the intensity of heat liberation during fricion.

The presence at the adjoining surfaces of oxide films and their thickness has an influence on the friction coefficient. Thin, but very hard oxide films, as a rule contribute

to the lowering of the friction coefficient; thick oxide films but less hard bring about its increase.

4. The Temperature Regime of Friction Surfaces and the Phenomenon of Seizing (Binding)

During the friction process, the temperature of the contiguous friction surfaces does not remain constant; it also varies within the friction surfaces. This is due to the fact that the energy utilized for overcoming the friction forces (molecular-mechanical interaction of surfaces) is first generated in the form of heat on the elementary physical contact surfaces. At these points, temperature peaks of short duration may appear, causing a sudden increase in the temperatures of the microprojection. These temperatures might drop just as quickly because of an intensive dissipation of heat from within the body to the surrounding medium. However, the average temperature of the friction surfaces will continue to increase during the initial period of the process.

Heat generation during friction is not limited to the surfaces of the points of physical contact. The deformation of the uneven surfaces, which absorb a certain portion of the energy during friction, also generates heat. Therefore, one can refer to the heat generating surface as a layer having a certain thickness.

A temperature field is created during friction within the limits of this layer, and also due to heat conductivity of the interior layers. In the immediate proximity of the point of physical contact, this field has a hemispherical shape; at a certain body depth, the isothermic surfaces of the individual points begin to form a uniform temperature surface (Fig. 13a).

At present, the necessary scientific means for accurate calculation of friction temperature fields are not yet available. Such calculations are also encumbered by the impossibility of accurately considering the boundary conditions during the heat exchange. The method for approximate calculation of the temperature is described in a series of papers devoted to this question (10,45). Some space is devoted to this problem also in Chapter 5.

It is important to emphasize here that the distribution of the temperature along the depth x (in the direction perpendicular to the friction surface) of the body is determined by a diminishing function (Fig. 13b).

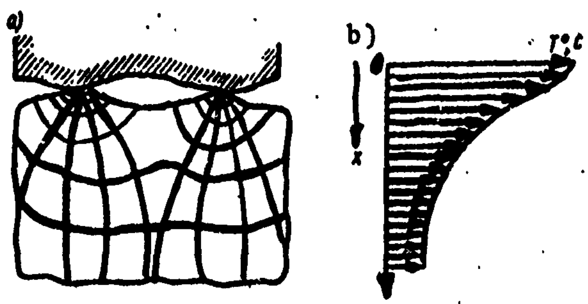

Fig. 13. Temperature field of the surface layer of the metal: a. - in micro-volumes; b - in micro-volumes (temperature distribution at depth x).

The increase in the temperature of the bodies, resulting from heat generation produced by friction, in turn introduces changes in the friction process. Thus, with heating to 200-300 degrees C, lubricants change their properties so that if marginal friction existed before, dry friction exists afterwards. In most cases this change is connected with an increase in the friction coefficient, friction forces, and heat generating energy. It usually brings about a further increase in temperature.

In crystalline bodies the increase in temperature up to values corresponding to the temperature of recrystallization results in a change of the physical characteristics of the bodies and, consequently, in a change in the friction coefficient.

Certain scientists (33) assume that the character of the friction process is determined not only by the temperature on the friction surfaces but also by the temperature gradient normal to this surface. It is known that in metals the mechanical properties, particularly the strength, depend on the temperature. Therefore, the gradient of mechanical properties always corresponds to the temperature gradient. If the mechanical gradient is positive, i.e., when the strength increases from the surface to the depth of the body, then the friction - caused failure of the surfaces has a localized surface character. With a negative strength gradient a deep failure occurs and the thickness of the heat generating layer is increased. It is probable that this has an influence on the phenomenon of binding (seizing).

I.E. Vinogradova thinks that binding during friction is a result of simultaneous action of several factors. In particular, she points out that seizing goes over to the "catastrophic process of binding" as the actual area of contact of the friction surfaces is increased. When this takes place, a sharp rise in the friction coefficient is observed.

In other words, the formation of seizing centers leads to a considerable quantitative change in the process, which is reflected by the friction coefficient. Apparently, this is also connected with qualitative changes in the process.

Actually, the formation of seizing connections between

two friction surfaces results in the creation of a tangential resistance force which prevents the relative movement of these surfaces even without normal pressure. However, this does not agree with the accepted notions of the friction phenomenon and friction force. The determination of the latter (34) is unthinkable without an indication of the role played by the normal pressure.

The difference between the tangential force indicated above and the friction force becomes evident when the friction welding process is reviewed from this standpoint.

If at the beginning of this process, before seizing has started, no other forces exist except friction, the rotation of one piece with respect to the other is resisted only by the moment of the exterior friction forces (after removal of the axial, i.e., normal load, the interlocking between the sections disappears), then at the end of the process after the permanent connection has been formed, the resistance to such rotation can in no way be explained by exterior friction (after removal of the axial load the permanent connection between pieces does not disappear); it rather corresponds to the notion of joint strength. At least this is how the strength of pieces is determined when testing them in torsion. Thus, in the friction welding process, the exterior friction is superceded at the end of the process by phenomena connected with the strength and interior friction forces of the material. It is logical to assume that this will have to be reflected in the laws governing friction welding.

These qualitative changes taking place in the welding process, must apparently be connected with the formation of unit seizure centers, since they form the basis for the creation of a permanent connection in joints of mechanisms and machines

that are subjected to friction forces (at failure) as well as friction welding. The seizure centers are created locally at first and then spread over the entire friction surface.

It can be seen from the above that the friction welding process is considerable more complicated than the processes usually encountered in machine joints subject to friction forces. It is governed by specific laws, the study of which has only begun.

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1. Based on the book by I.V. Kragel'skiy and I.E. Vinogradova (33) "Friction Coefficients", Mashgiz, 1955.

2. Some text books and handbooks still include these obsolete notions.

3. In equation (10) e is based on natural logarithms.

Chapter IV

HEAT LIBERATION DURING FRICTION WELDING

5. Analysis of Heat Liberation

It was noted in Chapter IV that the temperature regime of friction points in machines is very important. Many scientists agree that seizing during friction is due in a significant degree to the temperature increase at the friction point.

Even more important is the heat liberation during friction welding. In this case, the heat regime determines not only a set of phenomena taking place at the friction surface, but also the productivity of the process, strength of the welded joint, and, finally, the variables of the welding equipment.

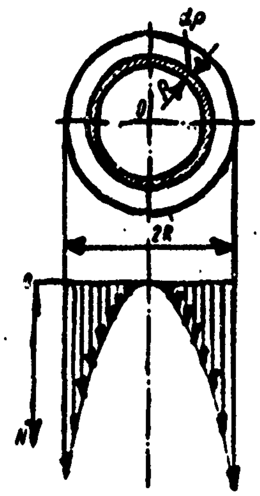


Fig. 14. Heat liberation diagram for friction welding assuming p = const., f = const.

The heat regime, in turn, depends on the intensity of heat liberation (power) during welding.

The analytical expression for heat power applicable to the most simple scheme of a friction welding process may be obtained by considering the heat liberation at an element of area of the friction surface, limited by the radii ρ and $\rho + d\rho$ (Fig. 14).

The elementary force

$$dF = pf\ dS = 2\pi pf\rho\ d\rho \qquad (11)$$

acts on this infinitely small area $dS = 2\pi\rho d\rho$.

The moment of this force around the rotation axis (point 0) is

$$dM = \rho dF = 2\pi pf\rho^2 d\rho \qquad (12)$$

The heat power in the investigated friction area eiement is found from the expression

$$dN \approx 1.02 dMn10^{-6} = 2.04\pi pfn\rho^2 d\rho 10^{-6} \qquad (13)$$

The following notations were used for equations (11-16):
F and dF - entire and element of force of friction in kg
M and dM - entire and element of moment of forces in kg mm
N and dN - entire and element of power kw
p - unit pressure in kg/sq. mm
n - relative rotation speed in RPM
f - friction coefficient.

If one assumes that the unit pressure p and the friction coefficient f in equation (13) are constant along the friction surface, and that the friction coefficient does not depend on the linear speed and on pressure, i.e. $p(\rho)$ = const. and $f(p, n, \rho)$ = const., then the heat liberation diagram $dN/d\rho$ would look like a quadratic parabola (Fig. 14). In this case, the maximum heat liberation is at the periphery of the friction surface; at the rotation axis such heat liberation is equal to zero.

Given the assumptions made, the integration of equations (12) and (13) yields following expressions:

for the moment of friction forces acting along the entire

friction surface

$$M = \frac{2}{3}\pi p f R^3 \qquad (14)$$

for corresponding power of heat liberation

$$N = \frac{2}{3}\pi p n f R^3 10^{-6}, \qquad (15)$$

for average unit power in relation to the unit surface friction (W/sq.mm)

$$Ny\partial = \frac{N}{\pi R^2} \approx \frac{2}{3} p f n R 10^{-3} \qquad (16)$$

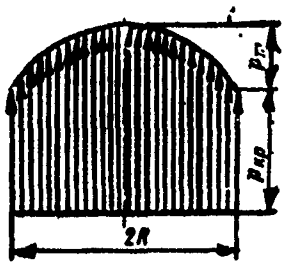


Fig. 15. The pressure diagram of compressed faces and mutually stationary annular rods.

In actuality, the unit pressure at the surface of two adjoining stationary bodies is not distributed uniformly. As is shown in references (2, 36), the pressure distribution curve is convex (Fig. 15) and for compressed faces of two stationary rods of annular cross-section with radius R can be described by the following equation:

$$p(\rho) = p_m\left(I - \frac{\rho^2}{R^2}\right) + p_{cr} \qquad (17)$$

The proportion P_m/P_{cr} determines completely the degree of convexity of this curve.

If one considers the instability of the unit pressure along the cross section then by substitution of equation (17) in equation (13) and replacing Pm by the average unit pressure, equal to the total applied force divided by the nominal friction surface ($p = P/\pi R^2$), the equation for the heat liberation diagram will be

$$dN = 2\pi fn\ [2p(1 - \frac{\rho^2}{R^2}) - P_{cr}(1 - 2\frac{\rho^2}{R^2})]\rho^2 d\rho \qquad (18)$$

The value of the resulting power of heat liberation can be obtained from the following equation:

$$N = \frac{2}{3}\pi fnR^3\ (\frac{4}{5}p = \frac{7}{15}P_{cr}) \qquad (19)$$

The more accurate diagram of heat liberation is a series of curves presented in Fig. 16. These curves, apparently, have a maximum, whose location is displaced along the abscissa depending on the shape of the unit pressure curves (or the relation p_m/p_{cr}, see Fig. 15). During the change of this ratio from zero to infinity, the heat liberation changes from 0.7R to R (curve 1 corresponds to $p_{cr} = p$, i.e. $p_m = 0$ or the case $p(\rho)$ = const., represented in Fig. 14). It is not difficult to note that in the more accurate version of power equation (19) the first member is similar in structure to the expression of ideal power (15) and is different only by the coefficient 4/5; the second member of equation (19) also points to the decrease in the value of the integral friction power as a result of making $p(\rho) \neq$ const. as compared with expression (15) where this was not done. (In this comparison, the cross section dimension and the magnitude of the applied force are assumed to be the same in both cases.)

Following conclusions can be made based on the analytical expressions for elementary and entire friction power:

1. The heat liberation at the friction surface is unsteady: in the center, at the rotation axis ($\rho = 0$), there is no heat liberation because the rate of the relative motion of the friction surfaces is equal to zero there;

at some distance from the center, the heat liberation curve (Fig. 16) is maximum, whose location (radius value) at

the surface is determined by the shape of the pressure diagram (Fig. 15), or, more precisely, by the ratio p_m/p_{cr};

on the periphery (where $\rho = R$) a decrease in the heat liberation takes place, if the magnitude of the actual unit pressure is significantly decreased;

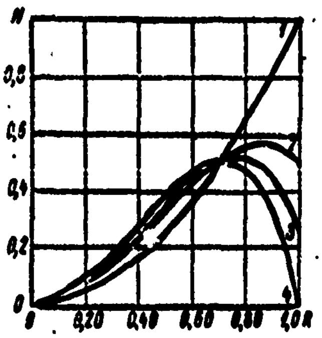


Fig. 16. Heat liberation power diagram during friction welding assuming $p(\rho) \neq$ const., f = const.
1 - $\frac{p_m}{p_{cr}} = 0$; 2 - $\frac{p_m}{p_{cr}} = 2$;
3 - $\frac{p_m}{p_{cr}} = 6$; 4 - $\frac{p_m}{p_{cr}} = \infty$

2. the intensity of heat liberation is determined by the linear rotation speed πR, the magnitude of the nominal unit pressure $p = R/\pi R^2$, the material properties and the condition of the friction surfaces (friction coefficient f), and, finally, by the magnitude of the surface friction πR^2;

3. it is apparent from equation (16) that the average heat liberation power along the friction surface does not depend on the magnitude of this surface.

Based on these conclusions, one may assume that the temperature, like the heat liberation power, is not constant along the friction surface. However, experimental studies of the temperature field during friction welding confirmed that this is true only in the initial stage of the friction process. At the same time, it was established experimentally that the temperature is equalized along the friction surface.

These studies confirmed the truth of the conclusion made above that it is necessary to consider separately the laws of

the initial and the final stages of heating during friction welding.

6. Temperature Distribution at the Friction Surface

The experiment conducted by the author (9) and then repeated by others (16, 51), made it possible to clarify the temperature change for various points on the friction surface (at different distance from the rotation axis) by oscillographic monitoring of thermal emf of semi-artificial thermocouples, which were installed into the samples previously. The samples were welded in such a way that during the entire welding process the hot junction of the thermocouples was always at the friction surface.

One of the oscillograms is shown in fig. 17. As a result of many experiments with the low carbon 20 steel samples, later repeated with other materials (16, 51), it was established that despite the theoretical instability of the heat liberation power (Fig. 16), the temperature in the butt (from center to the periphery) several seconds after the start of the friction process is practically equalized and its scattering does not go above 50-100 degrees C. The small time period of temperature equalization (3-5 sec.) at sample diameters of 20 mm and up did not permit the assumption that the temperature equalization is due only to the heat transfer from hotter points to colder points on the friction surface. The heat transfer can only partially contribute to such a temperature equalization.

The mechanism of this phenomenon is explained by the spontaneous redistribution during the friction process of unit pressure and power of heat liberation and, consequently, of the temperature. Actually, as was shown above, in the first moment of the friction process all forces applied to the samples are

felt only by a small number of projections with highest lengths. Huge local unit pressures lead to instant temperature flashes. However, the metal of these projections, which became plastic under the action of heat, is easily deformed at high pressures. It ceases to feel the force. The force is applied to new projections which are in contact. As a result, the intensity of heat liberation in the points of initial contact decreases and the sharp increases in temperature occur at the neighboring regions of the friction surface, and so on. This process spreads along the entire friction surface. Thus, the temperature at the surface is quickly equalized.

The dynamics of this phenomenon is easily followed in Fig. 18. It can be seen that with time the points of seizing spread out quickly and after 2 seconds from the start of friction cover the entire surface. It is important to note that the central part of the surface where the heat generation is minimum is not excluded from this process.

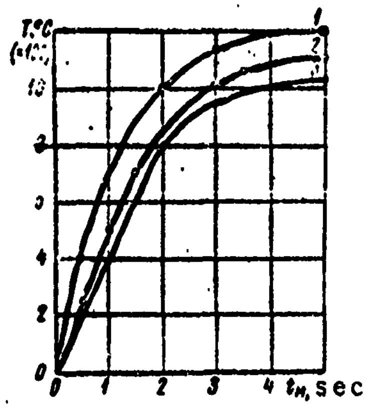


Fig. 17. The temperature change as a function of time for friction surface points at different distances from the rotation axis:
1-ρ = 8.5 mm; 2-ρ = 5 mm; 3-ρ = 0 mm (welding regime: 1000 RPM; p_n = 5 kg/sq. mm; low carbon steel, 20 mm diameter)

For additional checking of the phenomenon of the temperature equalization along the cross section a series of technical tests was conducted: the joining by friction of low carbon steel samples was performed at a welding regime which insured quite satisfactory quality of the welded joint. After

removal of burrs, the samples were cut (Fig. 19) into 2 by 2mm or 2.5 by 2.5mm templates. The templates were tested for strain and bending (static and impact). These tests do not meet the State Standard because of unusual dimensions of the samples tested. The results were useful for comparison of the quality of the welded joint in different areas of the friction surface. All templates cut from one sample, including those taken from the central part were equal in the welded joint quality.

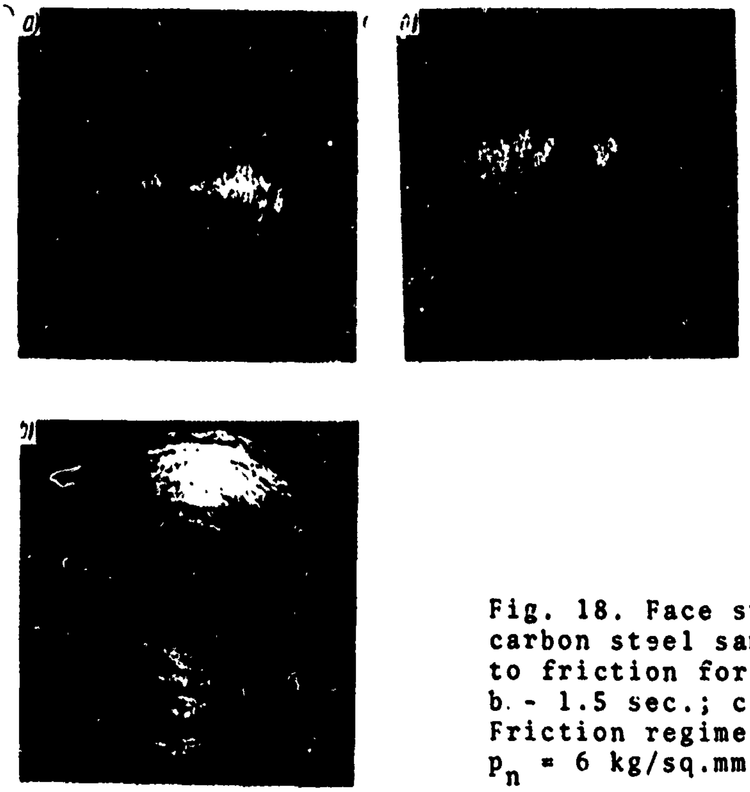


Fig. 18. Face surfaces of low carbon steel samples subjected to friction for: a - 0.5 sec.; b - 1.5 sec.; c - 2.0 sec. Friction regime: n = 1500 RPM; p_n = 6 kg/sq.mm.

Fig. 19. A sample of low carbon steel after welding and cutting into templates.

Thus, it was established that the deformation process of surface volumes of the metal during friction welding plays another important role because redistribution of the unit pressure along the friction surface, rapid (spontaneous) temperature equalization, and conditions for the formation of the welding joint along the entire cross section of the welding pieces are achieved.

From above, following conclusions can be drawn:

1. For the first 3-4 seconds, and sometimes less, from the start of the friction process, the unit pressure is redistributed spontaneously. As a result of this, the power calculation, even when using the more accurate equations (18, 19) can be performed only approximately.

2. The source of heat during friction welding can be considered flat with constant intensity along the friction surface. However, this occurs only after the end of the initial stage of the process, the stage of temperature equalization along the cross section.

3. The average stable temperature of the friction surfaces is in the range of 950-1350 degrees C according to the reduced data from the oscillograms of the low carbon steel welding.

The initial stage of the friction process is described by equations (18, 19). Only these relations make it possible to explain the following constantly observed phenomenon: colors of

dark-red incandescence appear inside the butt between the welding pieces approximately 0.6 - 0.8 R distant from the center at the beginning of the process and only then, in agreement with the above, spread out rapidly along the entire friction surface.

7. The change of Heat Liberation in Time

These studies were conducted in the laboratory. The test set-up was equipped with a device, which made it possible to observe and to note the magnitude of the moment of friction forces during the entire welding process.[1]

Because the product of the force moment M and the rotation speed n has the dimensionality of power ($N = kMn$), then during constant rotation speed the curve $M(t)$ can be considered as a curve of power change on another scale. At the same time, the area limited by the abscissa and two coordinates t_2 and t_1 is the energy for the period $t_2 - t_1$ because

$$\vartheta = \int_{t_1}^{t_2} N dt = k \int_{t_1}^{t_2} M n dt \qquad (20)$$

The tests were conducted by the author (9) using samples from low carbon steel with a 20 mm diameter, at unit pressures of 2 - 10 kg/sq. mm and rotation speeds of 240 - 3000 RPM. The results were checked using samples with different diameters. The welding, in each case, was performed using axial force, which was constant during the entire process. The force was first applied to the samples, then the samples were rotated. Numerous oscillograms of changes with time in force moments and power taken during various welding regimes (for instance Fig. 20) have the same curve shape.[2] Fig. 21 presents a characteristic curve of the force moment M (t) and superimposed curve of the speed of relative rotation n (t).

Fig. 20. Oscillogram of the welding process of low carbon steel samples (20 mm diameter). Welding Regime: n = 1500 RPM; p_n = 6 kg/sq.mm; 1 - force moment curve; 2 - upset speed curve; 3 - timing curve (50 Hz)

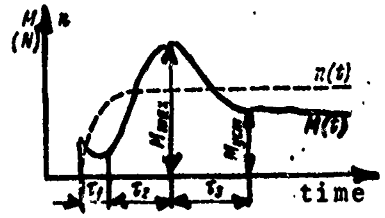


Fig. 21. Change in time of force moment M and rotation speed n during friction welding.

From the illustrations presented it is apparent that the heat power, as well as the magnitude of the force moment sharply change during the welding process, passing first through a minimum, then a maximum value and, finally, tending to some constant value at the end of the process.

The experimentally obtained curves of the change in heat liberation as a function of time (force moments and power oscillograms) are of interest not only in connection with the task of studying these changes. The analysis of the curves makes it possible to get some ideas about phenomena taking place at the the friction surfaces during welding. The initial phase of the welding process proceeds at low temperatures and is characterized by dry or marginal friction (friction coefficient $f \approx 0.1$ to 0.12). The small peak in the moment curve at the beginning of the process

($f_0 \approx 0.25$) corresponds to rest friction. The transition from rest to motion corresponds to an initially rapid and then a slower drop of the moment curve (time interval τ_1 see Fig. 21). The following rapid growth of this curve in the time interval τ_2 and accompanying oscillation of undetermined frequency, superimposed on the basic curve, can be considered as a sign of the beginning of the transition from dry (marginal) friction to pure friction (33).

As approximate calculations show[3], the average temperature of the friction surfaces is 100-120 degrees C at the beginning of the time interval τ_2. The temperature of the separate points may reach significantly higher values, during which the absorbed substances on the friction surface are changed (15).

Because of this phenomenon and as a consequence of baring of spots of pure metal on both friction surfaces caused by destruction of oxide films, it is possible to form areas [bridges] of separate seizing (3). However, in the process of continuous relative motion of surfaces these areas are destroyed immediately after their formation. The energy utilized for deformation appearing in form of heat contributes to the rise in temperature of the surface. This, in turn, alleviates progressive formation of new sources of seizing, which are again destroyed, and so on. The seizing process quickly grows. Fig. 18 presents the surfaces of several "canned" samples with different heating periods.[4] It is apparent from these photographs that the growth of the number of seizings and their spreading out along the surface rapidly increases with time. However, the finite dimensions of the friction surface prevent the limitless growth of the number of seizing points. Therefore, with time, this process having achieved a certain level, becomes steady.

Together with the increase in the number of separate seizings, a rapid increase in the force moment is noted by the oscillogram. This force moment is necessary for the destruction of these seizings. A corresponding temperature rise at the surfaces is also noted. The presence of a maximum in the moment oscillogram (Figs. 20 and 21) can be explained only by simultaneous influence of two oppositely acting factors on the process.

As one of these factors, one can take the above described first rapidly- and then gradually-decreasing growth of the number of separate seizings.

The other, opposite acting, factor is phenomena connected with temperature change. As a result of temperature rise, the friction moment decreases:

because of the decrease in the metal strength and, consequently, the decrease of the force moment and power, necessary for the destruction of seizing connections, which became less strong;

because of the appearance of liquid metal phase at the friction surfaces, which serves as lubrication and lowers the friction coefficient[5].

In both of these cases the action of the second factor, as well as of the first factor, is intensive at first. Then as the melting point is approached, the action is gradually slowed down. The heat transfer from the butt into the surrounding cold metal of the piece and also heat losses from the metal forced into the flash contribute to the above.

As a result of simultaneous action of the two factors mentioned above, the process unavoidably leads to self control: the moment and the power of friction reach certain stable values

(Figs. 20 and 21).

When considering the relations of temperature change as a function of time, it is convenient to conditionally divide the entire heating process during friction welding into three phases (Fig. 21): first (initial) phase, which is characterized by the predominance of the external (dry and marginal) friction - τ_1;

second phase, which begins with the appearance of seizing and is characterized by the process of vigorous increase of the number of points of separate seizing, - τ_2

third phase, which is distinguished by high temperatures and the tendency of the process to stabilization, - τ_3.

It is apparent, when considering the power oscillogram from the point of view of heat liberated in the various phases of the friction welding process that in the first and second phases the heat liberation is insignificant. In particicluar, calculations performed for the oscillogram presented in Fig. 20 yield the following results (in %):

amount of heat liberated in the first phase	1
" " " " " " second "	12
" " " " " " third "	87

One can consider that the heating of pieces to the state of increased plasticity, necessary for formation of a strong welded joint, occurs almost exclusively in the third phase of the process.

This very important statement was checked numerous times in different welding regimes by simultaneous oscillograms of the change in upset and the force moment. The experiments confirm completely the above statement: the beginning of the upset

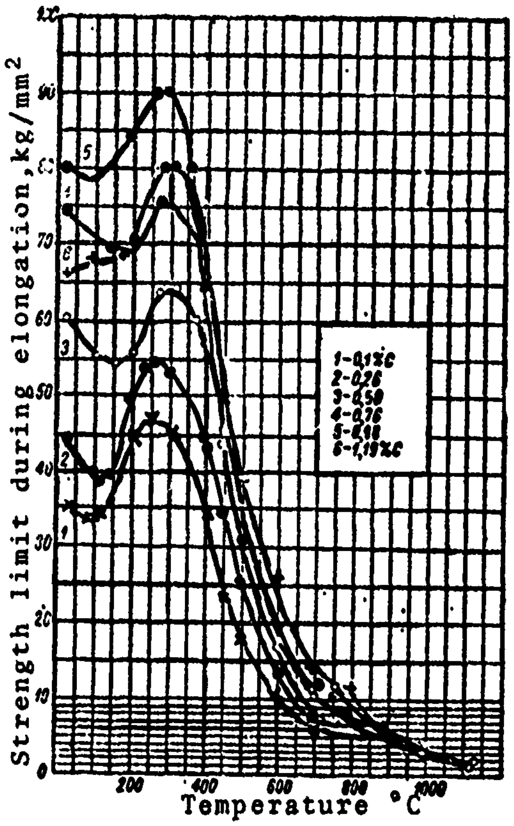


Fig. 22. The change in the strength limit of carbon steels as a function of temperature.

approximately coincides with the maximum force (power) moment.

Thus, one can state that in the first phase, external friction occurs which only initiates the intensive heating. The characteristic feature of the second phase is the heating of the thin surface layer of pieces and appearance of points of seizing. In the third phase, the seizing process spreads out along the entire friction surface, the intensive heating of the surface layers of the metal takes place and the accompanying plastic

deformation of the welding pieces occurs (forcing the metal in a radial direction). Thus proceeds the heating during friction welding. As was explained earlier, the heating is one of the necessary conditions for welding of metals and alloys. However, one cannot identify heating with the welding process, as one cannot identify the welding process with its result - formation of a welded joint. If the increase of temperature of pieces by friction begins already in the first phase, then the welding process begins from the moment of appearance of first seizings, i.e. only in the second phase. Then, the welding process intensifies with the intensifications of seizings and their spreading throughout the entire friction surface. The friction surfaces are completely prepared for formation of the welded joint. However, the welded joint cannot be formed as the relative motion (heating) continues and, together with the formation of metallic bends, their destruction goes on. The welded joint is formed only after the end of heat liberation (rotation). At this stage - the peening stage - the stationary and cooling pieces are subjected to external compression force. In a series of cases, the magnitude of the peening pressure, as compared with the pressure during heating, is higher.

8. The Dependence of Heat Liberation on the Rotation Speed and Pressure

Experiments conducted with the aim of studying the influence of the relative speed of rotation and pressure on the intensity of heat liberation during friction welding led to several unexpected but very interesting results.

It is usually considered that the intensity of heat liberation during welding should increase and the period of the process, with all other conditions equal, should decrease with increase

in the relative speed of rotation.

However, experimental relations obtained between the machine time of the welding process and the rotation speed (Fig. 23) in the significant speed range (800-3000 RPM) revealed the reverse: with increase in the rotation speed the machine time of the welding process increases. One can assume that this relation in the indicated speed range is practically linear. This is confirmed not only by timing of the process period but also by the external appearance of welded samples. The appearance of a "collar" indicates that with the decrease in the rotation speed the intensity of heating increases.

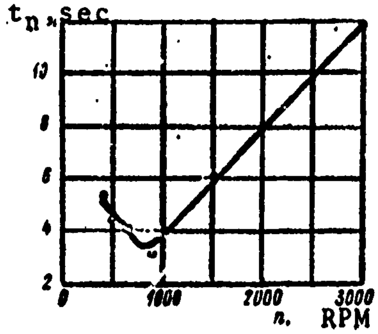


Fig. 23. The dependence of heating time on the rotation speed. Material: low carbon steel: 20 mm diameter; p_n = 5 kg/sq.mm, upset of heating 5 mm.

More convincing in this respect are oscillograms presented

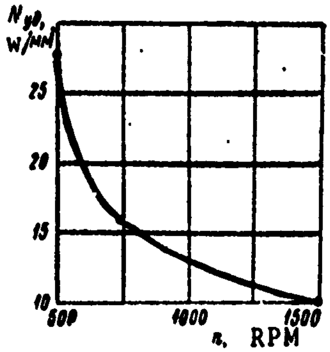


Fig. 24. The power of heat liberation depending on the rotation speed. Low carbon steel: 20 mm diameter; p_n = 5 kg/sq.mm; upset of heating 5 mm.

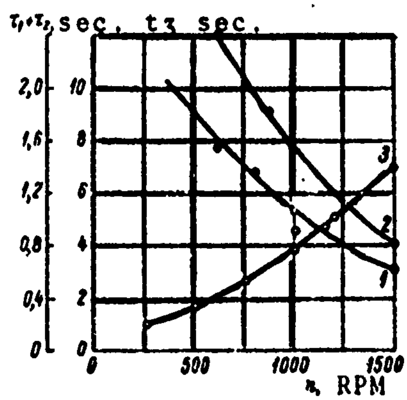


Fig. 25. The period of various phases of heating process depending on rotation speed. Low carbon steel: 20 mm diam.; upset 6 mm: 1 & 3 - p_n=6kg/sq.mm; 2 - p_n = 4 kg./sq.mm.

If one assumes that to heat a given piece to an assigned temperature a certain, completely determined, amount of energy is necessary, then from Fig. 24 the cause of the increase in the process time with increase of the rotation speed becomes apparent. This occurs because of the reduction in power.

The dip in the curve in Fig. 23 is clear from Fig. 25. At speeds of rotation below 800 RPM (this applies to regimes, sample materials and the sample cross sections studied) the prevalent influence on the process period is exercised by its initial stages (τ_1 and τ_2). At speed of rotations greater than 800 RPM the prevalent influence on the process period is exercised by its third phase. Fig. 25 is of interest because of variable character of relations represented there. A change in the time of initial phases of the process by changing the rotation speed is opposite in character to the change in the time of the third phase. If the first relation can be approximately described by equation

$$\tau_1 + \tau_2 \approx \frac{A'}{n}, \tag{21}$$

showing the inverse relation between $\tau_1 + \tau_2$ and the rotation speed, then the second relation

$$\tau_3 \approx B'n + C' \tag{22}$$

reveals almost linear character of change in $\tau_3(n)$ throughout a wide range of rotation speeds (here A,B,C are constants).

If one assumes that the melting of metal does not occur at the friction surfaces during normal speeds for friction welding (this is confirmed by the author (9) as well as by other researchers (16, 51)), then from the two causes of the drop in the moment and power in the third heating phase mentioned on page 12 only one remains: the decrease in the shearing resistance with the increase of temperature of the metal surface layers.

If this is true, then following conclusions can be drawn, which confirm the above assumptions: during the friction welding process, beginning with the first phase and ending with the start of formation of welded joints, the phenomenon of the surface friction (marginal, then dry and pure) yields gradually to all phenomena connected with the destruction of forming metallic bonds, i.e. with shear strength of the metal under temperature conditions of the butt):

in accordance with this, laws governing the friction welding proces in the initial and final stages have to be changed.

It should be noted that the relations between the heating time and the rotation speed mentioned above were obtained by the author from experiments conducted with constant magnitude of heating upset. It was assumed that this magnitude is an important parameter of the friction welding process, which determines the properties of the joint obtained. It must always be lower than a certain magnitude. If the welding regime is established only up to the time of stabilization of the heat liberation and is independent of deformation, then, as is shown in reference (16), the relationship between the necessary heating time and the rotation speed is different from the one above.

9. More Precise Equations of Heat Liberation

The results of experiments described at the end of the previous section revealed a possibility to correct analytical expressions of the moment and power of heat liberation. The correspondence of equations (14) and (16) with the relation presented in Fig. 24 ($N_{y\delta} \approx$ const.) was possible with the following condition:

$$f = \frac{k}{(np)^2}. \qquad (23)$$

In agreement with the statements above, the magnitude f at the end of the heating process cannot be called a friction coefficient. It is more correct to speak of shear strain corresponding to a given temperature condition of the butt metal. This thought was expressed earlier (12) by the author and was then developed by V.P. Voinov in his dissertation (17). The character of the relation τ_{cp} (nR) for pipe cross sections is close to the relation described in equation (23).

The simultaneous solution of equations (12) and (13) with the equation (23) and consequent integration leads to following finite results:

$$M = 2\pi p \frac{k}{n^2} R \, [\text{kg} \cdot \text{мм}]; \tag{24}$$

$$N \approx 2\pi p \frac{k}{n} R 10^{-6} \, [\text{kw}] \tag{25}$$

or

$$N \approx 2p \frac{k}{nR} S 10^{-6} \, [\text{kw}]; \tag{26}$$

$$N_{\text{уд}} = \frac{N}{S} = 2p \frac{k}{nR} 10^{-3} \, [\text{w}/\text{мм}^2]. \tag{27}$$

In all these expressions k is constant and has the dimensionality of the square of linear velocity (sq.mm/sq.min.). Its numerical value depends on the properties of the welding materials; for low carbon steel, in particular[6], k = 1.6 x 10^7sq.mm/sq.min. The equations obtained agree satisfactorily with experimental data and can be recommended for practical use during selection of friction welding regimes. We also use them constantly during calculation of basic parameters of newly designed equipment for friction welding.[7]

At the XXI Congress of the International Insvitute of Welding (Warsaw, 1968) a report by Dr. Nakamura (Japan) was discussed. The following expression for the friction moment was

proposed in this report as the result of careful studies by the author for low carbon steel welding:

$$M = 290p^{0.58}R\left(\frac{n}{1000}\right)^{-1.2}\ [\mathrm{kg}\cdot\text{мм}], \tag{28}$$

from which

$$N \approx k'\frac{R\sqrt{p}}{n^{0.2}}, \tag{29}$$

where k' - constant.

In structure, equation (20) is similar to equation (25). However, the results of these equations do not coincide. The causes of this disagreement are still unclear and should be studied.

Footnotes to Chapter IV:

[1]The usually stationary (during friction welding) sample is installed in a special case with ball bearings. It is prevented from rotation during welding by a lever fixed at one end to the case. The free end of the lever rests on a support. The force moment at the face surfaces of the samples is balanced by the reaction moment of the support applied at the end of the lever. Elastic deformations of the lever body occurring are proportional to the friction force moment. They were recorded by a loop oscillograph with the help of tensometric (wire) sensors glued to the lever and corresponding amplifying equipment. At the same time, the axial force (by tensometric sensor) and the relative rotation speed (by tachogenerator, rigidly connected with the shaft of the machine) were recorded.

[2]Later, other scientists (16, 51) used this method of study during welding of other metal combinations (rapid cutting steel with structural steel, aluminum with steel and other).

[3]These calculations can be performed, for instance, using the theory of therma process by N.N. Rykalin (45) or using data of other researchers (10, 59, 67, 72).

[4]At the end of the specified time of heating (friction) the samples were quickly separated without stopping the rotation to study the condition of the cooled surface.

[5]Although the value obtained by calculation and experiment of the averaged temperatures of the steel friction surfaces are in the range 950 to 1350 degrees C, it should not be excluded that points of these surfaces with highest loads may reach melting temperatures.

[6] In the first edition of the book K was incorrectly given as 8×10^7 sq. mm/sq. min.

[7] When calculating the unit power the following requirement should be maintained (because the power is constant and independent of the magnitude of the welding parts): p/nR = const: for low carbon steels this value is 5×10^{-4} kg/(mm/min).

Chapter V

BASIC PARAMETERS AND RECOMMENDED REGIMES IN FRICTION WELDING PROCESS

10. The Role of Plastic Deformation in the Friction Welding Process

Regardless of the point of view and opinions about the character and nature of the forces arising between two solid bodies during their approach and, consequently, about the mechanism of the formation of welded joints in the solid phase, it should be considered established at present that the deformation plays a most important role in this process.

As was shown above, the joining surfaces can be brought together to such a degree that the actual area of their contact becomes commensurate with the nominal area only because of the crumpling deformation of the micro-projections. The heating has a large significance in this process as a means of bringing the surface layers of the metal to a state of increased plasticity and consequently facilitating the formation of the welded joint.

Of great significance is the deformation of metal surface layers on a macro-scale during the process of formation of welded joints at temperatures below the melting point. The destruction of oxide films covering the contacting surfaces and the removal of the fragments of these films from the butt into the flash is due to plastic flow of the metal in the butt plane, i.e. to deformation developing in the relatively thick layers of metal measured in tenths of a millimeter.

The indicated functions of deformation occur also during friction welding. However, in this case the deformation of metal

plays considerably more important role than in other types of welding in the solid phase. During friction welding the outside energy necessary for welding is converted to heat as a result of deformation and the destruction of metal surface volumes. Thus, their deformation, is to a significant degree a function of temperature and heat liberation. On the other hand, the deformation is itself the cause of heat liberation. Consequently, during friction welding there is not only the direct connection heat → temperature → deformation but also the reverse connection deformation → heat → temperature.

This reverse connection leads to the closing of the heat liberation cycle, which is the cause of its self control and the tendency to a stable value. This value is determined for a given metal by external (independent) process parameters: the rotation speed and forces applied along the axis (unit pressure).

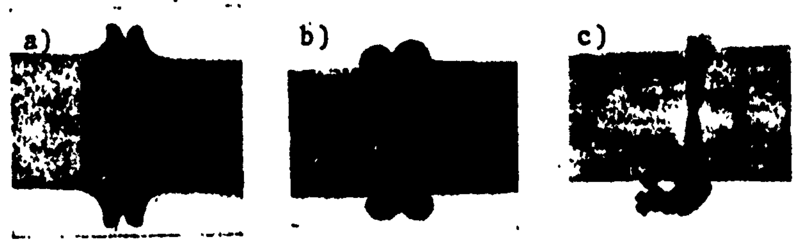


Fig. 26. Microsections (diametric cross section) of samples which were friction welded. Low carbon steel: 20 mm diameter; p_n = 5 mg/sq.mm; upset 5 mm. Speed of rotation: a - n = 3000 RPM; b - n = 800 RPM; c - n = 400 RPM.

This reverse connection - heat liberation as a result of deformation - determines the specific role of deformation during friction welding, which distinguishes this process from other types of pressure welding.

The other feature of deformation in the friction welding process is, as was clarified earlier, the automatic (spontaneous) temperature equalization at the friction surface.

The deformation should be divided into two following aspects: a. deformation of micro-volumes should be differentiated from deformation in micro-volumes; b. the crumpling (creep) deformation should be differentiated from shear deformation or torsion.

Experience and elementary calculation show that crumpling deformation plays only secondary role in the energy balance of the friction welding process; the mechanical work (the product of the axial force and the upset) spent for pure crumpling of the micro-projections and for forcing metal from the butt, is not more than 2-3% of the entire energy spent for welding. Consequently, the dominant role is played by torsion deformation (shear of microprojections, breaking of atomic bonds in the friction plane, more or less deep extraction of metal particles from the surface of one part during relative transfer of the other part) in the energy balance of heat liberation.

The deformation of the microprojection shear to some degree helps the approach of the surfaces and the multiplication of the number of separate contacts and thus alleviates the problem of bonds formation. Therefore, the deformation of shear, not only crumpling, is very important in the physical aspect during the friction welding process.

Micro and macro-deformations should be differentiated because the processes of bond formation between the surfaces (independent of their nature) are inherent in the submicro-volumes of the metal and no relatively thick layer is theoretically necessary for this process[1]. At the same time, the heat liberation

during the friction welding - depending on the regime process - occurs in micro- and macro-volumes of metal. The process regime, in this case, determines the character of interaction of rubbing surfaces. During slow speed of relative motion of friction surfaces depth extraction of metal particles occurs during the surface wear process (this, according to Kragel'skiy (32), is connected with small temperature gradients and mechanical properties of metal in the direction normal to the friction surface); during relatively high velocities of motion there is no depth extraction. It is substituted by the process of polishing of surfaces when only minute particles of metal are extracted (17, 29).

In the first case, significantly thick metal surface layers (up to several tenths of a millimeter) are present in the heat generation process; in the second case - the heat generation process is due mainly to the destruction of the surface bonds and the thicknes of the heat generating layer can be minimum.

An apparent paradox can be explained by the dependence of the layer thickness on the process regime: it was established experimentally that with the increase in the rotation speed the temperature of the friction surfaces increases somewhat, despite the fact that the power spent for welding decreases noticeably (Fig. 24). The fact is that during small rotation speeds in the heat generation process significantly larger volumes of metal are involved (Fig. 26) than during higher rotation speeds. This causes an increase in the consumption of energy and power. However, a relatively thick layer of metal, which was heated to higher temperatures, is easily forced out carrying with itself a significant part of heat from the butt into the flash. As a result, the temperature at the friction surfaces, where colder metal arrives during the deformation process, is lower than

during increased rotation speeds.

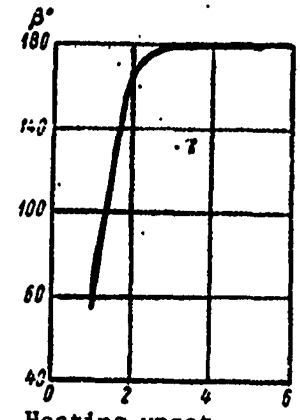
However, independent of the character of deformation (crumpling or shear) and at what scale (micro- or macro-) they take place, the role of the deformation of metal in the friction welding process is of extraordinary importance and varied. Without the necessary degree of deformation, it is impossible to obtain good quality joints.

It was shown that during a given friction regime (rotation speed and unit pressure) the upset should not be lower than a certain value. In the example shown in Fig. 27 the bending angle of 180 degrees is assured during testing of the welded joints with an upset of not less than 3 mm.

The following thoughts confirm the importance of the plastic deformation of metal in the butt zone for formation of good joints.

As was shown above, the diagram of normal pressure is bell-shaped in the initial stage of heating during friction (Fig. 15). It was also made clear that such shape of the diagram is due to the action of friction forces at the surface of the contact and that at the peripheral zones of these surfaces, the magnitude of these normal pressures is relatively low. Because the pressure is determined by the resistance of metal to creep, then as the metal is heated p_{cr} decreases tending in the limit to zero. Because of this, one can observe a defect in the joints at small values of heating setting during friction welding. This defect is usually called "ring non-fusion". It is a ring located at the periphery of the friction surface. Within its borders, the welding joint is not of high quality because of insufficient normal pressure.

Fig. 27. The dependence of the bending angle (during testing of welded joint) on the upset. Low carbon steel: 30 mm diameter; p_n=4.0 kg/sq. mm; p_{np}=12 kg/sq. mm; n = 1000 RPM (9)



However, the ring non-fusion is usually absent in joints, which are distinguished by relatively large size of the collar (flash), i.e. such joints where the deformation process was sufficiently complete. This is explained by the fact that as the flash is formed the friction surfaces increase in size and the zone of lower normal pressures at the periphery is displaced beyond the initial boundary of the part into the collar (fig. 28). The metal of the collar cools comparatively fast and becomes less plastic. Its resistance to creep grows and the value of p_{cr} increases. Thus, the formation of the flash during friction welding contributes to the equalization of the normal pressure diagram for the butt and to improvement of the quality of the welded joint.

This feature of the process is the basis for the use of the ring chuck, so-called upset tool, during friction welding of parts made from materials with different plastic properties at welding temperatures (see chapter VII).

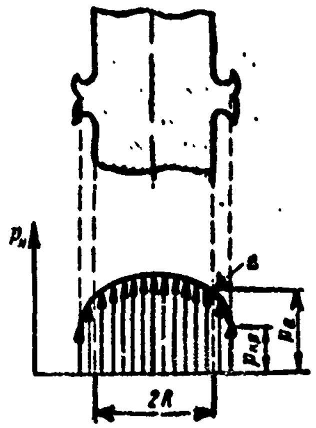


Fig. 28. A scheme of the temperature distribution along the cross section of annular samples: $p_a > p_{cr}$ in the flash.

Thus, the plastic deformation of metal during friction welding is really a necessary condition for formation of high quality joints. When the bases of the theory and technology of the friction welding were developed, the plastic deformation was accepted as one of the basic parameters of the process. As its measure, the magnitude of approach in the axial direction of the welding parts, upset, was adopted. Another parameter of the process could be the temperature in the butt or, for instance, the power of heat liberation. However, these parameters are not independent variables. As is apparent from chapter IV and the present chapter they are determined for a given pair of metals by the speed of relative motion (rotation) of the friction surfaces and the magnitude of the heating pressure.

Therefore, the rotation speed and the magnitude of the pressure (unit) during heating were adopted as the other two basic parameters. Sometimes these two parameters are called energy parameters. At the same time, the upset is considered a technological parameter. Such a division of basic parameters of the friction welding process into energy and technological parameters is somewhat conditional. During more careful consideration of the phenomena occurring at the friction surfaces during welding, the inconsistency of such a strict division of basic parameters is revealed. The connection between them is more complicated. This is why earlier (see chapter IV) the impossibility of their arbitrary variation was noted during selection of the optimum welding regime. For instance, the unit pressure is not only a parameter determining the magnitude of heat liberation. Dependent on its change (at the same temperature fields in the welded parts) is the degree of deformation of metal and, consequently, the unit pressure is also a technological parameter.

The shape of the temperature field in the parts depends to a significant degree on the intensity (power) of heat liberation.

One can imagine two welding regimes during which the maximum temperatures in the butt would be the same and the initial heating in depth (in the direction normal to the friction surface) would be different. This is not hard to achieve by variation of the product p_n, i.e. by changing the power of heat liberation, with corresponding change in the time of action of the heat source. The different (in magnitude) initial heating of parts in depth will be reflected unavoidably in the width of the thermal effect zone and the metal structure in this zone, i.e., finally, in the characteristics of the welded joint. Thus the two energy parameters under close examination may be included among the technological parameters of the friction welding process.

Sometimes it is thought that together with the rotation speed and unit pressure, the time should be selected as the third basic process parameter, i.e. the time of heating (the action time of the heating source). This though is based on the fact that for a given heat power (rotation velocity and unit pressure), the time of heating for a given pair of parts completely determines the magnitude of energy spent for welding, the shape of the temperature field, and the entire heating regime of the process. The deformation is only a function of this regime.

From the point of view of the practical use of friction welding, the use of time as the third parameter of the process (instead of upset) can be considered expedient in a series of cases (see section 12). However, such substitution of parameters does not account for the role of several secondary factors, whose influence can change the friction coefficient and, consequently, power of heat liberation, even if the unit pressure and the rotation speed are not changed. Especially, this is

important for initial phases of the process. The role of the pressure is not accounted for. It can be varied maintaining the power of heat liberation unchanged, thus influencing the magnitude of upset.

Usually the magnitude of upset or the duration of heating is used in the friction welding machines for automatic stoppage of heat liberation. The selection of one of these for such regulation of the process depends on a series of conditions. This problem is discussed below. Here, it should be emphasized once more that arbitrary variation of one of the basic parameters of the process is absolutely inadmissible and that welded joint of satisfactory quality can be obtained only under condition of correctly selected combination of all three basic parameters.

It is important to note also that once the parameters of the welding regime are chosen, they should be maintained strictly constant. Because, for instance, a decrease in the established heating time or the upset magnitude may lead to incomplete removal of oxides from the butt or to non-uniform heating of the cross section of the welding parts and an increase to overheating of the metal, growth of grains in the thermal zone and impairing of metallic characteristics of the metal. As a result, decrease in strength of the welded joint may occur in both cases. An analogous effect may be obtained during instability of pressure and rotation speed.

Finally, there is one more, fourth, process parameter - peening pressure.

The peening stage, which occurs right after the end of heating stage (i.e. in the moment of braking of the rotating

part), is characterized by the fact that the metal, which, as a result of heating, is at the required temperature at the butt and sufficiently heated along the axis of the part, is subjected to action of an external force. This is necessary for final approach of parts and for "curing" voids, which may have been formed during the relative motion of the contacting surfaces. In Fig. 9 the importance of peening pressure for obtaining high-quality welded joints is shown.

Below, in corresponding sections of the chapter, the principle of selection of basic process parameters of the friction welding is discussed.

11. <u>Preparation of Parts for Welding</u>

The initial condition of the friction surface may influence the selection of basic process parameters such as the degree of contamination, roughness (purity of processing), shape.

The indicated factors have little influence on the process and its results (the quality of the formed welded joint) during friction welding of parts from the same material. On the other hand they can exert significant influence on the process and the quality of joints during welding of parts from materials of different physical and chemical properties.

During welding of similar metals and alloys various substances may exert some influence on the "binding" of heat liberation. These surfaces may be substances adsorbed by the friction surface, contamination, and oxide films which unavoidably cover any metallic surface including surfaces to be welded. The degree of ntamination may be different from part to part. The duration of the first phase changes, i.e. the time necessary for removal

of lubricants and contaminations from the friction surface or time necessary for formation of first points of seizing. When the heating is regulated as a function of time, the different duration of the first phase of the process may lead to time loss in separate cases or in any case will cause instability in the duration of all the phases. This in turn may reflect on the instability of heat liberation and consequently on the quality of the forming joint. One way to fight this understandably undesired phenomenon is to regulate the heating process as a function of upset instead of as a function of time (see section 12 of this chapter). If this is impossible for any reason, then the parts should be cleaned from grease and contamination, for instance, by wiping their face surfaces with a clean rag before welding. In most cases this is completely sufficient and only in some cases as an exception is it necessary to degrease these surfaces using chemical means.

The indicated influence of grease films and dirt on the destabilization of welded joints is more apparent at slow rotation speeds, when the duration of the first and second phases of the heating process determine the general time balance (see Figs. 23, 24, 25). Therefore an increase in the relative rotation speed may reflect favorably on the stability of the quality of the welded joints of parts which were poorly degreased before welding.

The increase in pressure also has a favorable effect in these cases.

Thin oxide films on the joining surfaces do not harm the welded joint during welding of parts of similar metals and have no effect on the heating process. They are quickly destroyed during friction and their fragments are carried out from the butt by metal forced out radially.

But slag is not tolerated on the friction surfaces. Surfaces of parts which were subjected to forging, stamping or other types of thermal processing before welding should be cleaned from slag by any acceptable method.

The preparation of surface faces for friction welding may be accompl ·hed by different methods: turning on the lathe, cutting with scissors and under pressure, cutting with the saw or sand disc, and others. In this respect, the friction welding process for similar metals is not difficult. Specially designed tests were conducted, which made it possible to determine that during friction welding of two rods from similar metals, the perpendicularity of the ends of the rotation axis is not necessary. A deviation of 5-7 degrees has no noticeable effect on the quality of the welded joint. It is only necessary to regulate the process as a function of time. Imperfections due to processing of parts on the lathe or saw have no effect on the friction welding process and its result. All small projections at the face of the surfaces disappear instantly at the start of the welding.

When joining two parts butt to butt having the same diameters but made of materials having different degrees of plasticity at welding temperatures the requirement for the preparation of faces is somewhat complicated. The part from harder and less deformable material requires more rigid tolerances on the face processing. If one of the parts during welding is hardly deformed at all (for instance, steel during welding with aluminum), a very careful facing of such a part is required. The facing should not exceed 0.2 mm. Otherwise a poor quality joint may result. Such processing is best performed in the chuck of the welding machine. The welding machine should have a special cutting support for this purpose.

Careful facing is also necessary for friction welding of T-shape joints even from similar metals. Especially if a pipe cross-section part is welded to a flat surface. In the last case the non-perpendicularity of the friction plane leads to a loose (although sometimes strong) joint.

There are no requirements during friction welding for the side surfaces of parts. They can be fatty, contaminated, covered with slag, or rust. All this in no way reflects on the properties of the joint obtained. This is a feature of friction welding which compares favorably with other types of welding. Some general recommendations on selection of the welding regime are presented below.

12. The Selection of the Heating Regulation Method in Friction Welding

All contemporary friction welding machines, automatic as well as semi-automatic, perform the welding process strictly automatically. They stop the heat liberation according to a pre-assigned program. As already mentioned, this program can be a function of heating time or the upset magnitude. Some types of equipment make it possible to transfer from one of these methods of heating regulation to another with the help of a simple switch-over in the control circuit of the machine.

As already pointed out, the regulation of the process as a function of upset is recommended in cases when the face surfaces of parts to be welded are insufficiently clean or covered with a layer of rust. This is especially pertinent if the welding is to be performed at slow rotation speeds. During such regulation, the incidental changes in the duration of the first phase will not reflect on the flow of the process, because heating will be stopped (independently of time passed since its start) only after

the actual heating upset will achieve a pre-assigned magnitude. This magnitude is set on the scale of a special monitoring device.

If parts have burrs or other projections on the contact surfaces whose heights are commensurate with upset magnitude, then the upset regulation is not permitted. The approach of the surfaces due to wear of the burrs will be read by the monitoring device as beginning upset. It can happen (if the machine was set for optimum value of upset) that the welded joint will be not fused. This can be avoided by setting the machine for upset with advanced reserve. However, such an operation regime leads to the lowering of productivity and excessive use of metal. Sometimes, this can result in the decrease of the quality of the welded joint, if the metal of the piece is sensitive to overheating. Welding of parts with burrs of various height will unavoidably lead to making of joints with variable actual upset at the same setting of the machine and, consequently, to variable quality. This is, naturally, undesirable and sometimes not permissible. In these cases the regulation of the process as a function of time is recommended.

Thus, to obtain joints of high and similar (constant) quality during selection of the heating regulation method for friction welding one has to start with condition of the preparation of parts for welding and consider the condition of their face surfaces.

13. The Selection of the Rotation Speed

The power spent (Fig. 24) and the productivity of the process (Fig. 23) depend on the relative rotation speed.

The size (thickness) of the heat generating layer depends

on the relative rotation speed and consequently the temperature field in the welding parts. V.P. Voinov showed in reference (16) that this is due to the dependence of the character of wear of the friction surfaces on the speed of their relative rotation. In a comparatively slow speed range, deep extractions of metal particles occur. At fast rotation speeds a polishing effect is observed (wear of a very thin metal surface layer. It is shown in the same reference that because of this there may be changes in the welded joints. Thus, it was observed during study of friction welding samples made from 20 steels that with an increase in the rotation speed, the viscosity of the butt metal was increased.

It is shown also, in the same work, that with an increase in the rotation speed the machine time of the welding process is decreased, (the steady values of the force moment and power are achieved earlier than at lower speeds) and the heating upset and the amount of metal which is forced into the flash is significantly lowered. Consequently, the dimensions of the collar are also lowered. The tendency to weld with a higher speed of rotation was observed once in the USA.

There exist also works which take the opposite approach showing the advantages of welding at reduced rotation speeds.

Thus, the problem of effective selection of rotation speed during friction welding is under discussion. However, moderate regimes and, from our point of view, optimum rotation speeds which we proposed earlier have been used successfully by a large number of Soviet enterprises for a long time now. The efficiency of these regimes was confirmed also by studies conducted in Great Britain, the Federal German Republic, and also by some Japanese data.

We have adopted the moderate rotation speeds on the basis of the results of studies presented in part in Figs. 23, 24, 25. We recommend these speeds for the following reasons:

Very slow rotation speeds, as experiments have shown, lead to the dominating role of the first and second phases of the heating process in the general balance of machine time of the welding process. When this occurs, as was shown in section 11 of this chapter, the total duration of these phases depends to a significant degree on the initial condition of the surfaces. Therefore low rotation speeds (especially during regulation of the heating as a function of time) may lead to welded joints with sharply different mechanical properties of the butt and thermal effect zone of the metal.

At relatively slow rotation speeds comparatively thick metal layer takes part in the heat generation, which is heated to the increased plasticity state; the metal flows out in large "drops" (Fig. 26c). This may be the cause of voids in the butt.

At slow speeds of rotation (compared with moderate speeds) the power spent is increased and at the same time the productivity of the process is decreased.

At increased rotation speeds the amount of power spent is reduced (Fig. 24). However, the bearing (support) points of the friction welding machine operate under significantly more difficult conditions as compared with conditions at moderate speeds.

The quality of the welded joints obtained depends only to a small degree on the rotation speed throughout a sufficiently broad range of change according to the data obtained by the author for low carbon steel welding.

Thus, for each combination of metals there is a certain

spindle rotation speed.

The recommended [illegible] speeds of rotation which we have selected as a result of a careful analysis of experiments are in the [illegible] m/sec. range. The product of rotation speed (n, rpm) and spindle diameter d_k, mm of the existing [illegible] lies within the limits

$$[illegible]$$ [illegible]

For [illegible] we recommend nd_k [illegible] 10^4 ([illegible] speed of rotation [illegible] m/sec.).

As an exception, for certain [illegible] we recommend higher speeds.

For [illegible] .... nd_k = [illegible] to [illegible] 10^4

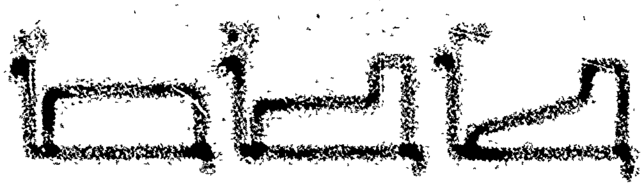
For [illegible] .... nd_k = [illegible] to [illegible] 10^4

Following reasons are given in justification of the increased rotation speeds:

The increase in rotation speed makes it possible to reduce [illegible] the [illegible] time.

At increased speeds, the [illegible] and the [illegible] of the [illegible] are reduced, the time for the following operation, the [illegible], is reduced.

One can agree with these arguments. However, one should consider that at these speeds the [illegible] of the [illegible] is necessary before [illegible]. Thus, the [illegible] of the [illegible] of the [illegible] and [illegible] can be [illegible] at the [illegible] of the [illegible] of [illegible] and [illegible] the [illegible] of each [illegible] to be [illegible]



The moment of the increase in unit pressure during the step cycle should coincide with the end of the heat liberation (rotation). However, in practice it is sometimes early and sometimes late. It is hard to achieve exact coincidence. The latter is preferable because the butt metal has no time to cool down and the peening effect is not changed. However, in the first case (early) the increase in pressure during continued rotation causes an excessive (although brief) increase in the heat liberation and concurrent increase in the upset, the metal consumption, and also additional loads on bearings. The use of the step pressure cycle (with increased pressure during peening) has technical advantages, such as improved mechanical indicators of welded joints. It also makes it possible to conduct the heating process at somewhat lower unit pressures as compared with the constant pressure cycle. Thus, equipment with less power can be utilized. Of course, machine time of heating and the width of thermal effect zone are increased[8]

The step pressure cycle somewhat complicates the design of the machine. However, this is compensated by the advantages listed above.

It is often not necessary to use the step pressure cycle when welding simple parts made of similar materials with the same cross-sectional area, for instance welding low carbon steel. Sometimes even compositions which are very difficult to weld (for instance rapid cutting steel with construction steel) can be successfully welded using the constant pressure cycle[4]. However, these examples are exceptions from the general rule. In most cases increased pressure is necessary during peening.

Usually, the proportion of the peening pressure p_{np} and pressure during heating p_{n} is obtained from following relation

$$\frac{p_{np}}{p_n} \approx 2. \qquad (31)$$

However, cases are known when a satisfactory quality of welding joints was obtained only when

$$\frac{p_{np}}{p_n} = 3{,}5 \div 4{,}0. \qquad (32)$$

The numerical value of the unit pressure during heating is usually between 1 and 8 kg/sq. mm (depending on the properties of welding materials. In rare cases the pressure during heating is 10 kg/sq. mm. The peening pressure varies between 2 and 15 kg./sq. mm. In very rare cases it can go up to 25 kg/sq. mm.

Thus, the comparatively narrow range of pressures can be explained by the fact that during the low heating pressure the process is long. At its end the heat is distributed throughout a large area of metal. The structure of the metal is impaired. During very high heating pressures the temperature in the butt is lowered[7]. This is not always favorable for the joint properties. However, one can imagine cases during welding when this phenomenon can be used to advantage. The peening pressure should not be very small also. It should also not be very large because the heated (plastic) metal will be forced out during the peening process. Colder metal layers will be in contact. As a result, the quality of welded joints might be unsatisfactory.

Thus there is a certain zone of optimum values for the heating as well as the peening pressures for each combination of metals. Concrete values of these magnitudes are determined from experimental data.

15. The Selection of the Heating Upset Magnitude

As was mentioned above, the upset is one of the basic parameters of the welding process. The mechanical properties of the joints depend to a significant degree on the heating upset which occurs during welding.

For example, Fig. 27 shows the effect of the upset magnitude on the bending angle of welded joints, whose strength and plastic properties are exposed well during this type of testing. The curve shows that to obtain good welding results it is necessary that heating upset should be not less than a certain value.

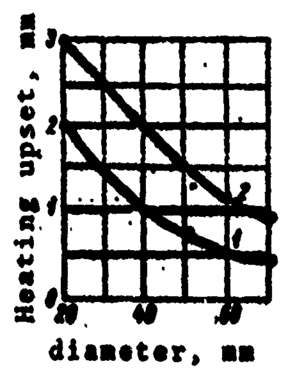


Fig. 30. The dependence of upset during heating on the diameter of welding part. 1 - minimum, 2 - recommended.

This fact and the deformation and its measure, the upset, discussed in the first section of this chapter are the cause that the upset magnitude was assumed to be independent of the rotation speed and of the diameter of the welding parts. In all tests, the magnitude of the upset was assumed to be constant. In particular, when the author was studying the friction welding of low carbon steel the heating upset was assumed to be 5 mm.

Later, our studies and studies by other researchers established that the necessary magnitude of the heating upset depends on the rotation speed and on the diameter of the welding parts.

It was noted above that it is not expedient to continue heating after steady heat liberation was achieved. At the same time (16) it was shown that the achievement of steady value of power of heat liberation occurs at different time. It depends on the rotation speed. As rotation speed is increased the time and the upset of heating are decreased.

The optimum values of heating time and heating upset can be determined easily in each case experimentally even under plant conditions. The moment when heat liberation process reaches a steady state can be timed using an ammeter in the power circuit of the motor (17). The view on the magnitude of the upset as a function of the diameter of the welding parts was also changed. Fig. 30 shows the result of a study of the above relation for several steels. The experimental method for determining the optimum upset and time of heating can be performed under plant conditions.

16. The Direction and the Development of Calculation Methods for Selection of Optimum Friction Welding Regimes

In a very general form the basic recommendations for selection of the friction welding regime were presented in previous section. The possibility of selecting a regime is limited by these recommendations and by tables of recommended regimes given below. Both, the recommendations and the tables are based on accumulated experience. There are no mathematical means as yet for determining the optimum friction welding regimes. Only the first steps have been made in this direction.

The equations (24) through (27) which were corrected by experiments determine with sufficient degree of accuracy the necessary motor power of the welding machine as a function of

pre-assigned process parameters. Or they can be used in reverse, to find a combination of parameters which will allow welding of a given part on a given machine.

However, these formulas cannot meet more stringent requirements, for instance to determine a combination of optimum parameters for welding a given part. These equations include several variables. The experience in the friction welding field shows that if these parameters are changed, even if certain relations which do not change the result are preserved between them, the quality of the welding joints changes.

The absence of a sufficiently developed theoretical base is characteristic not only of friction welding but also of other types of pressure welding. At the present time, very important and useful attempts are being made to develop universal ideas about the mechanism of formation of the welded joint in solid phase and their mathematical interpretation.

Among such attempts are the recently published formulas by K.A. Kochergin (30), which according to Kochergin should make it possible to find general relations between the parameters, which determine the formation of joints during pressure welding. In particular these formulas attempt to determine the time for formation of joints.

The fact that such formulas have appeared should be considered as progress in the right direction. However, practical use of these formulas is hardly possible at present time. Kochergin thinks that the constant and initial conditions may vary. Calculations using these formulas show that results can change by several orders of magnitude when variations occur. This, of course, is not satisfactory.

M.Kh. Shorshorov and his associates (56, 57) developed a hypothesis of joint formation in the solid phase. The hypothesis is based on the contemporary theory of metals. This hypothesis was already mentioned in Chapter II. At the present time it is being made more precise by the authors. However, the hypothesis is based on a mathematical analysis which allows certain calculations for various types of pressure welding.

However, specific features of friction welding, which were described above (p. 69) do not permit the use of Shorshorov's hypothesis. This is due at least to two circumstances:

First, expressions (3) and (4) (see p. 26) were obtained assuming only static crumpling of microprojections by pressure applied normal to the contact surfaces and using the laws of creep theory. During friction welding, as was already established above beside the creep phenomenon (under normal static load), the deformation of the shear of microprojections is taking place during the dynamic process of surface displacement. This is not taken into account in Shorshorov's formulas.

Secondly, calculations were done based on the creep laws for metals under action of two independent variables - pressure and temperature. During friction welding, the heat liberation and the temperature are the essential result of destruction of formed and forming points of seizing, i.e. the temperature is a factor determining the first stage of the process and is itself a result of the second stage and cannot therefore be considered an independent variable. Such a reverse chain of events is not considered by the Shorshorov hypothesis and was not reflected in the mathematical interpretation of the hypothesis in the equations (3) and (4).

It is possible that in the distant future these difficulties may be overcome.

It should be noted, however, that calculations of the duration of the formation process of a joint in the solid phase are very interesting from the theoretical point of view and are necessary for some other types of pressure welding from the practical point of view. However, they are of less interest for friction welding from the practical point of view.

A different approach should be adopted in case of friction welding. The calculation of temperature in the butt as a function of process parameters and properties of the welding materials is very often necessary in friction welding. The reverse case is also true, i.e. determination of basic parameters of the welding process for a given pair of parts as a function of a given temperature.

An approximate analytical solution of this problem was performed long ago (10, 45, 67).

If one assumes that

1. the unit intensity of heat liberation at the friction surface is constant in time;

2. the thermo-physical constants of the welding materials are constant in the temperature interval occurring during welding;

3. the thermal flux from the butt to the pieces being welding is parallel to the axis of the piece (heat exchange with the surrounding medium and losses of heat to the flash do not occur) and rods are semi-infinite;

4. the initial temperature of the rod is equal to zero;

5. the beginning of the coordinates is in the friction plane and the x-axis coincides with the axis of pieces (axis of rotation), then the equation for the temperature field in the pieces (rods with equal diameters made from the same material) may be as given below:

$$T(x;\ t) = \frac{q\sqrt{t}}{c\gamma\sqrt{\pi a}}\left\{e^{-\frac{x^2}{4at}} - \frac{\sqrt{\pi}x}{\sqrt{4at}}\left[1 - \Phi\left(\frac{x}{\sqrt{4at}}\right)\right]\right\}, \qquad (33)$$

where T = temperature in degrees C of the point with coordinate x (cm) at time (t) after the start of heat liberation

q = unit power of heat liberation

$c\gamma$ = volume heat capacity

a = temperature conductivity coefficient in cm^2/sec.

Φ = complex function

The temperature in the butt is found from a much simpler expression if in eqn. (33) x = 0

$$T(0;\ t) = \frac{q\sqrt{t}}{c\gamma\sqrt{\pi a}}. \qquad (34)$$

If this expression is solved together with expression (27), then for calculation of temperatures in the butt as a function of process parameters of heating one obtains the following equation:

$$T = k'' \frac{p_n}{nR}\sqrt{t}, \qquad (35)$$

where k" = a constant in agreement with assumptions made

p_n = pressure during heating in kg/mm^2

n = rotation speed in RPM

2R = cross section diameter of welding parts in mm.

The equations obtained are suitable only for comparatively rough calculations. They require more precision because the assumptions made about the constant value of power with time and across the cross section are true only at the end stage of the heating process. When the expression was derived only external friction laws were considered. The properties of the welding material are reflected only in the unclear k" coefficient.

Besides, the calculations performed with these equations

do not yield well-defined answers for selecting the process parameters. They only make it possible to determine their desired correlation.

V.P. Voinov made a successful attempt to connect the mechanical characteristics of the metal of the welding parts with the heat liberation process parameters in some of his works (16, 17). He conducted his studies using thin-wall pipe samples to exclude the influence of the variable radius and to make the linear velocity of the relative displacement of surfaces practically the same for all points of cross-sections (friction surfaces) during the experiment.

Developing the aforementioned thought (12) on the steady moment (in the third phase of the heating) as a function of the shear strength of butt metal (which in turn is a function of the temperature in the butt) the author (17) showed that the destructive shear stress can be determined by the following equation:

$$\tau_{н} = \frac{2M_{уст}}{S_0 D_{ср}}, \tag{36}$$

where M_{ycm} = the value of the steady moment in third phase of the process

S_0 = the initial area of the cross-section of pipe sample

D_{cp} = average diameter of the annular cross-section of the sample.

When investigating the influence of the linear speed v of the relative motion of samples on the value of M_{ycm} it was established that for pipes of different size (18 x 3, 30 x 3, 35 x 3) all points of the destructive shear stress τ_{cp} as a function of linear velocity v and at constant heating pressure p_n form a general curve (Fig. 31) independent of the sample diameter and the rotation speed.

Comparing these data with the relation for τ_n^t (T) for the same steel (Fig. 32) it is not very difficult to obtain relations between the temperature at the butt and the linear velocity of rotation for various values of the heating pressure.

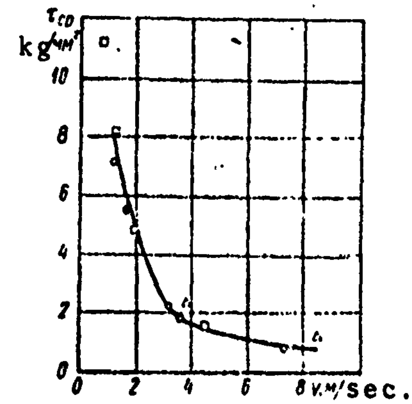


Fig. 31. The dependence of the destructive shear stress on linear velocity of rotation for pipe samples made from low carbon steel □ - 18 x 3, o - 30 x 3, Δ - 35 x 3.

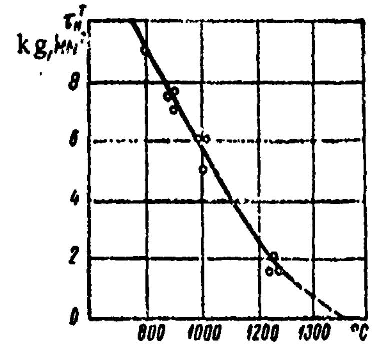


Fig. 32. The change in resistance to shear for low carbon steels as a function of temperature.

After correlating graphically all these values and introducing an additional parameter t_{nycm} (heating time to attain a steady force moment), V.P. Voinov obtained a nomogram for calculation of the maximum temperature in the butt and for welding regime parameters (Fig. 33).

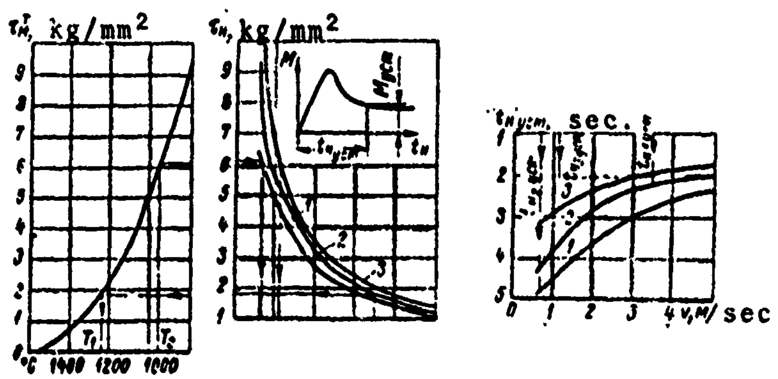


Fig. 33. Nomogram for calculation of temperature in the butt as a function of friction welding parameters. Low carbon steel pipe samples: $1-p_n=1$kg/sq.mm; $2-p_n=4$kg/sq. mm; $3 - p_n = 8$ kg/sq. mm.

With the nomogram and the use of equations (33), (34), and (35) for the temperature field one can determine the temperature values at any point of the thermal effect zone. In addition, one can obtain the metal structure in this zone.

The achievement of the nomogram is its universality for a given type or group of materials. It should be compiled only once using samples of one size selected arbitrarily.

The deficiency of this method is that it can only be used for one type of material and that it becomes necessary to conduct new experiments for compiling of new nomograms for each new material considered.

Besides, it is not known yet if the nomogram can be used in a more common case - friction welding parts with continuous cross-sections. Nevertheless, the creation of this nomogram should be considered as the first step in the direction of finding calculation methods for determining the optimum regimes of friction welding.

Not so long ago a method was developed for determining the maximum temperature in the butt. This method is based on the notion of a "quasi-stable" process of welding at the end of the third phase of heating. We noted, and Japanese researchers noted, that the curve for the relation of change for the heating upset δ_n as a function of time always has a characteristic shape presented in fig. 34. At a certain time, coinciding with the achievement of steady force moments, the rate of heating upset $d\delta_n/dt$ becomes constant. The experimental studies of the temperature fields show that together with the achievement of the steady force moments the rate of spreading of the heat along the axis of the welding rods becomes equal to the rate of their upset and, consequently, that the temperature field becomes

stabilized in space.

The author calls this steady process "quasi-stable". This process can be represented on the outside as a stationary (in space) temperature field into which welding rods are supplied at a constant rate $d\delta_n/dt$.

This condition, from the other point of view, can be evaluated as a condition of dynamic thermal equilibrium, where the amount of heat liberated is exactly equal to heat losses during the same time (heat losses occur mainly along the axis and into the metal of the welding parts and are also due to heat removal from the butt together with the metal forced into the flash). If one imagines (Fig. 35) that the curve ad characterizes the temperature distribution along the length l of the welding rod and that the friction surface (the heat source) is at point o, then, due to upset during time Δt_1 the rod is displaced relative to the stationary (in space) temperature field by og = dc. The new points b and c will lie on the curve of the steady temperature field.

Fig. 34. Typical shape of the curve for change of upset with time. Point a - the start of quasi-stable process.

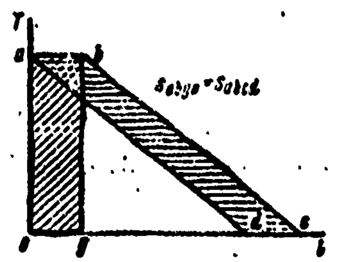


Fig. 35. The determination of energy consumption during quasi-stable welding process.

If the upset rate during the quasi-stable process is constant and equal to $og/\Delta t = dc/\Delta t$, and in the limit $v_{oc} = d(\delta_n)/dt$,

it can be seen from Fig. 35 that, independent of shape of the temperature field curve, the amount of heat consumed in a unit of time can be found from the following equation:

$$\frac{dQ}{dt} = c\gamma T_{max} S \frac{d(\delta_N)}{dt}, \tag{37}$$

where $c\gamma$ = volume heat capacity of the metal

S = the cross-section of the welding part

T_{max} = temperature in the butt when the steady force moment is achieved:

$$T_{max} = \frac{\frac{dQ}{dt}}{c\gamma S \frac{d(\delta_N)}{dt}} \tag{38}$$

or

$$T_{max} = \frac{q}{c\gamma \frac{d(\delta_N)}{dt}} = \frac{AN_{\mu\vartheta}}{c\gamma \frac{d(\delta_N)}{dt}}, \tag{39}$$

where q - unit consumption of energy per unit area of the cross section of the welding part for a unit of time.

Thus, after determining the experimental consumption of energy for the welding of a given material and heating upset rate, one can determine from expression (39) the temperature in the butt.

This was published and experimentally confirmed for the first time in a work by L.A. Shternin (59) when he investigated friction welding of steel with aluminum.[8] His conclusions were then checked by A.I. Khristoforov (51) during an investigation of friction welding rapid-cutting steel with construction steel.

Usually, during the welding of two parts made from different metals the metal of only one part is deformed. The magnitude of the friction surface during the entire process is not changed because the second part is practically not deformed. Therefore,

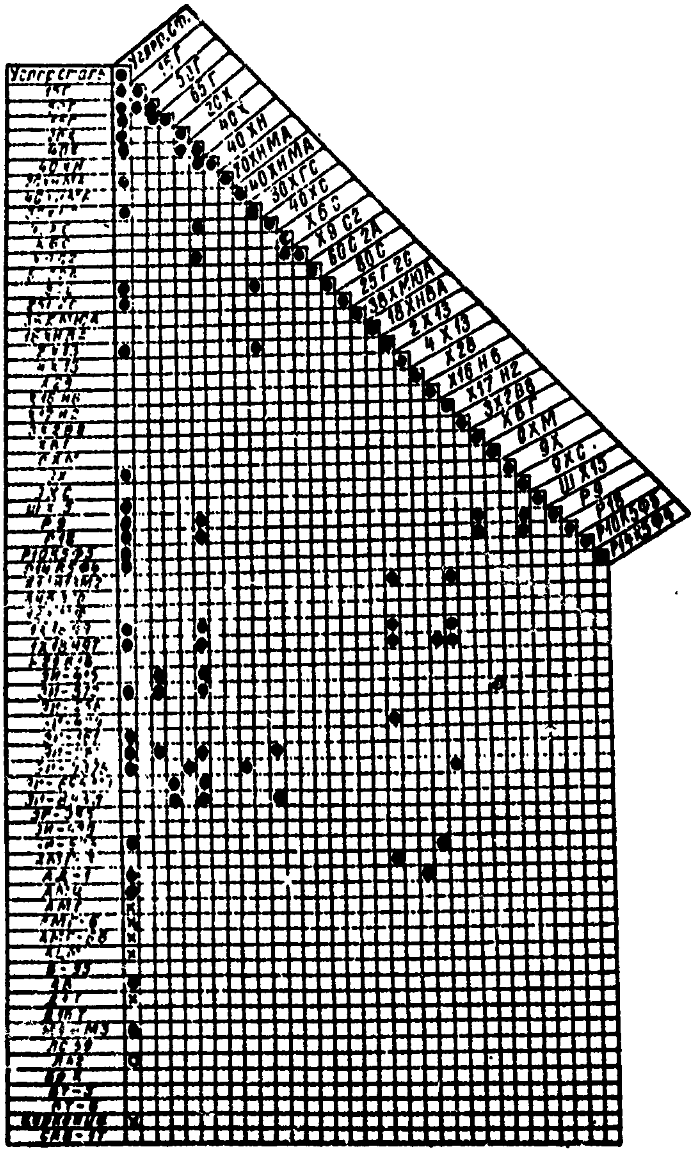
one can introduce the initial value of the friction surface into equation (37) $S = S_0$. During the friction welding of similar materials the deformation occurs symmetrically relative to the butt plane and the size of the cross section in the butt is increased gradually as upset increases.

Therefore, in this case, the actual increased, value of S should be substituted in equation (37) corresponding to the instant of the end of the heating process. Experiments performed by the author showed that under these conditions equation (37) yields satisfactory results. However, practical difficulties arise when determining the magnitude of the friction area at the end of the heating process. Thus, the method of temperature calculation based on the quasi-stable process can be practically used only in the case of welding different metals.

Based on the foregoing, one can draw the conclusion that mathematical tools now available are not perfect and do not allow the determination of the friction welding process parameters by calculation. This problem remains current. Up to now it can only be solved by semi-empirical methods and by using regimes recommended by experimental considerations.

17. Recommended Regimes of Friction Welding

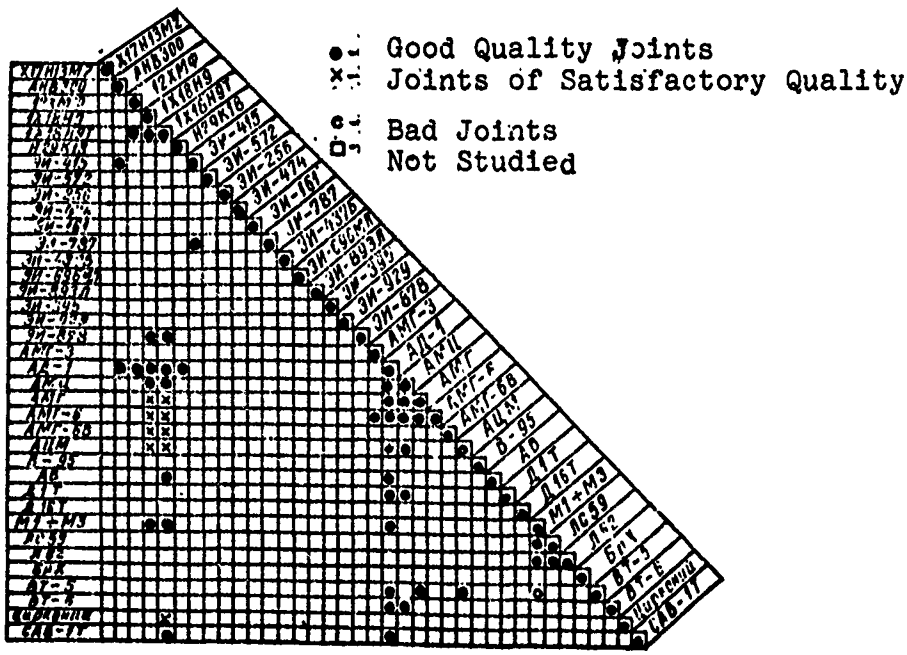
According to some researchers (35), seizing is basically possible between any metals. Based on this, one can assume that friction welding of any given metal pair is also possible. It is sufficient to create for this the necessary conditions, to select the welding regime. The majority of materials studied and used in practice can be joined succesfully with the help of friction welding. Among these are also those that cannot be welded at all or with large difficulty with other welding methods (aluminum with steel, copper with steel, austenite steel with



perlite steel, and other combinations). However, one encounters, rarely, such composition of metals (alloys), which do not have quality joints when friction welded. Some of these cannot be friction welded at all. The causes for this are not clear. It was noted above that the theory provides no answer to this question as yet.

To determine the practical possibility of friction welding of various metals and alloys numerous experimental studies were conducted. Their results are given in Table 1.

Table 1



A Table of Friction Welding Regimes of Certain Similar Materials — Table 2

Welding materials	Unit pressure in kg/mm²		Upset in mm		Heating time in seconds	Rotation speed in RPM	Unit power (stable) in w/mm²	Diameter of welding parts in mm
	Heating	Peening	Heating	Peening				
Carbon steel	5	10	3,5	5,8—6	6—6,5	1000	9	20
15G + 15G	5	10	3	5,3	6	1000	—	20
50G + 50G	3	6	3	5,5—6	7	1000	—	30/38
20Kh + 20Kh	5	12	3	5,6—6	8	1000	5	20
40Kh + 40Kh	6	12	3	5—5,5	8,5	1000	—	20
40KhN + 40 KhN	4	8	3	4,3	3,5—4	3000	—	12
40KhNMA + 40KhNMA	10	22	3,5	4,5—5	8—9	1000	9	25
20KhNMA + 20KhNMA	4,0	15	4	7,5	7,0	1000	6	20
60S2 + 60S2	7	14	3	4,5—5	10—11	1000	—	20
80S + 80S	9	18	4	7—8	4	1000	8	14
30KhGSA + 30KhGSA	8	16	3	5—5,5	5—6	1000	—	25
38KhMYuA + 38KhMYuA	10	20	4	—	2,5	1500	—	10
2Kh13 + 2Kh13	10	20	3	5,5	6	1000	—	20
9KhS + 9KhS	10	20	3	4,5—5	15	1000	—	30
Kh9S2 + Kh9S2	4	8	3	3,5—4	3,5	3000	—	12
ShKh15 + ShKh15	5	14	3	5	11	1000	—	25
EI161 + EI161	13	26	4	6,5	8—9	1000	—	20
EI415 + EI415	10	20	3	5	4,5	1000	—	20
EI572 + EI572	12	24	3	5—6	11	1000	15—16	20
EI474 + EI474	8	16	3	—	6—7	3000	—	10
EI787 + EI787	12	24	4	5,5	15—17	1000	15—16	20
1Kh18N9T+1Kh18N9T	7	17	3	5,3	3	1000	—	18
Kh17N2 + Kh17N2	7	14	3	4,8	8—9	1000	—	20
EI395 + EI395	11	22	4	4,9	18	1000	—	20
EI929 + EI929	15	30	2	—	3,5—4	1000	—	20
EI878 + EI 878	6	21	4	6	15	1000	—	20
AD1 + AD1	5	10	5	8—9	3—4	1000	—	20

A Table of Friction Welding Regimes of Certain Different Materials

Table 3

Welding materials	Unit pressures in kg/mm² — Heating	Unit pressures in kg/mm² — Peening	Upset in mm — Heating	Upset in mm — Peening	Heating time in seconds	Rotating speed in seconds	Unit power (stable) in w/mm²	Diameter of welding parts in mm	Overhang of the part from upset side
Steel 20+Steel 30	5	10	3,5	5,6—5,8	7	1000	10	20	—
Steel 20+Steel 45	5	10	3,5	5,0	10	1000	6—7	20	—
15 G + Steel 20	5	10	3,5	6	6—7	1000	—	20	—
15G + Steel 45	5	15	3	5	7	1000	—	20	—
50G + Steel 20	5	15	3,5	5	7	1000	—	20	—
50G + Steel 45	5	15	3,5	4,5—5	7—8	1000	—	20	—
20Kh + Steel 20	5	12	3	5,5	8	1000	4,7	20	—
20Kh + Steel 45	5	12	3	5	8	1000	5	20	—
40Kh + Steel 20	5	10	3,5	5—5,5	12	1000	—	25	—
20KhNMA+Steel 20	1,2	15	4	7,2	10	1000	5	20	—
R9 + KhVG	10	20	—	3	30	1000	—	30	3
R9 + Steel 45	8	16	—	2,5	11	1000	—	20	2
R9 + 40Kh	10	20	—	2,2	8	1000	—	18	2
R18 + KhVG	10	20	—	3	30	1000	—	30	3
R18 + Steel 45	10	20	—	2,5	12	1000	—	22	2
R18 + 40Kh	10	20	—	2,2	9	1000	—	18	2
R18 + 9KhS	12	24	—	3	15	1000	—	30	2—2,5
R10K5F5+Steel 45	8	16	—	3,0	11	1000	—	21	2
R14K5F4+Steel 45	8	16	—	2,8	12	1000	—	21	2
Kh9S2 + 40Kh	4	8	3	3,5	3,6	3000	—	12	—
ShKh15 + Steel 20	5	14	3	6—6,5	8—9	1000	14,7	25	—
ShKh15 + Steel 45	5	14	2,5	5—6	7—8	1000	15	22	—
EI161 + Steel 20	13	26	—	4,5—5	11	1000	16,5	21	3—4
EI161 + Steel 45	13	26	—	4,5	11	1000	16,5	21	3—4
EI415 + 40Kh	6	21	3	5,5	4,8	1000	—	20	—
EI415 + 40G	6	21	3	5	4,8	1000	—	20	—
EI572 + 40Kh	6	21	—	2,3	9	1000	—	20	2
EI572 + OKhM	6	21	—	1,8—2	9	1000	—	20	1,7—2
EI474 + 2Kh13	3	20	2,5	3,5	6	3000	—	10	—
EI787 + Steel 20	6	21	—	2,5	9	1000	—	20	1,7—2
EI787 + 50G	7	21	—	4	12	1000	—	20	3—3,5
EI787 + 40Kh	6	21	—	3,5	10	1000	—	20	3
EI787 + EI415	12	24	—	2,5	12	1000	14—15	16	2
1Kh18N9T+Steel 20	6	21	—	3,2	9	1000	—	25	2
1Kh18N9T+Steel 45	6	21	—	3,5	9	1000	—	25	2,5
1Kh18N9T + 40Kh	6	21	—	4	9	1000	5—6	25	3—3,5
1Kh18N9T + 2Kh13	6	21	—	4	9	1000	5—6	20	3—3,5
1Kh18N9T + Kh17N2	6	21	—	4	9	1000	6	20	3
1Kh18N9T + 12KhMF	6	21	6	9	5	1000	—	25/20	6
Kh17N2 + 40KhN	6	21	—	3	9	1000	6	20	2
Kh17N2+Kh17N13M2T	6	21	—	4	9	1000	6	20	2—3
EI696M + 40G	6	21	—	2,5	11	1000	—	20	2
EI893L + 40G	6	21	—	2,5	11	1000	—	20	2
EI893L + 40 KhS	6	21	—	2,5	11	1000	—	20	2
1Kh18N9T+EI878	6	21	4	5—6	12	1000	—	20	—
AD1 + Steel 20	5	10	10	16	3,0	1000	—	30	16
AD1 + 1Kh18N9T	5	10	10	16	2,8	1000	—	26	—
AD1 + AMts	5	10	10	19	3,2	1000	—	24	—
AD1 + M2	3	20	3	7	5	1000	—	20	2
AMts + D1T	5	10	10	15	2,8—3	1000	—	30	15

Mechanical Properties of Welded Joints — Table 4

Welding Materials	Critical point in kg/mm²	Viscosity in kg/mm²	Bend angle in degrees	Destruction of bend test occurred
Steel 20+Steel 20	38—49	8—10	180	No destruction
Steel 20+Steel 45	38—49	—	180	" "
Steel 45+Steel 45	66—68	2,7—3,7	80—120	At t.e.z.
15G + 15G	41—42	—	180	No destruction
15G + Steel 20	42	—	180	" "
15G + Steel 45	46	—	—	—
50G + 50G	63—68	—	110—180	At t.e.z.
50G + 15G	41—46	—	—	—
50G + Steel 20	40—42	—	180	No destruction
20Kh + 20Kh	59—63	—	160	At t.e.z.
20Kh + Steel 20	39—44	—	160—180	No destruction
40 Kh + 40Kh	82—95	—	60	At the butt
40Kh + Steel 20	38—46	—	180	No destruction
60S2 + 60S2	66—75	—	—	—
80S + 80S	105	—	30	At t.e.z.
30KhGSA+30KhGSA	101	6,5	100	"
38KhMYuA+38KhMYuA	110	—	50	"
2Kh13 + 2Kh13	50—52	—	180	No destruction
R18 + Steel 45	59,5—61,4	—	—	—
R18 + 40Kh	60—62	—	—	—
R18 +9KhS	61—62	—	—	—
Kh9S2 + Kh9S2	82—90	—	—	—
Kh9S2 + 40KhN	—	—	35—73	At the butt
ShKh15 + Steel 20	42—47	—	120—160	At t.e.z.
EI161 + Steel 20	48	—	180	At steel 20
EI161 + Steel 45	60—62	—	160—180	At t.e.z. Steel 45
EI572 + EI572	59—62	3—3,5	180	No destruction
EI572 + 40Kh	62—65	3—3,5	180	" "
EI572 + OKhM	62—64	3,75—4,5	180	" "
EI787 + EI787	—	—	180	" "
EI787 + Steel 45	45	—	180	" "
EI787 + 40Kh	71—76	3—6,1	—	—

Mechanical Properties of Welded Joints — Table 4 (con't)

Welding Materials	Critical point in kg/mm²	Viscosity in kg/mm²	Bend angle in degrees	Destruction of bend test occurred
1Kh18N9T+1Kh18N9T	58—62	—	180	No destruction
1Kh18N9T+ Steel 20	38—49	—	180	" "
1Kh18N9T + 40Kh	62	—	45	At the butt
1Kh18N9T + 2Kh13	62	—	180	No destruction
1Kh18N9T + Kh17N2	61	—	90	T.e.z. Kh17N2
1Kh18N9T + 12KhMF	—	—	180	No destruction
Kh17N2 + Kh17N13M2T	61	—	45—60	T.e.z. Kh17N2
EI395 + EI395	—	—	180	No destruction
EI929 + EI929	126	—	50—60	T.e.z.
EI696M + 40G	60—64	3,4—5	—	—
EI893L + 40G	60—68	5,4—7	180	No destruction
EI893L + 40KhS	50—53,6	4—7,1	180	" "
EI878 + EI878	71—72	—	180	" "
Kh18N9T + EI878	56—58	—	180	" "
AD1 + AD1	8—10	—	180	" "
AD1 + Steel 20	8—10	—	180	" "
AD1 + AM_{ts}	8,3—8,9	—	180	" "
AD1 + D1T	8,8—9,7	—	180	" "
AD1 + 1Kh18N9T	8,9—9,5	—	180	" "
AD1 + ATsM	8—10	—	180	" "
AD1 + M2	8—10	—	180	" "
AM_{ts} + D1T	16—17	—	180	" "
L62 + L62	42—50	10—15	180	" "
Br.AMts9-2+Br.AMts9-2	50	—	70—90	At t.e.z.

NOTES: 1. T.e.z. - Thermal effect zone.
2. During testing forelongation the destruction in all cases took place at the base metal, which was less strong than the two welded metals.

The dark dots symbolyze combinations which give good quality joints. The light rings present bad quality joints. Rings with crosses inside represent combinations which could not be friction welded at all. Combinations with no symbols were not checked.

The joints with mechanical properties in the seam metal and the heat affected zone which were not worse than the properties of the base metal are included by us among good quality joints. Joints whose strength was below that of the base metal were considered bad quality joints.

Selected and experimentally checked welding regimes for certain most frequently used metal combinations, which give good quality joints for similar metals are listed in Table 2. Table 3 gives the same for dissimilar metal combinations. The mechanical properties of welded joints corresponding to these regimes are listed in Table 4.

Footnotes to chapter V:

[1]Practically, because of rough protrusions at the surfaces of parts, it is necessary to ensure upset during friction welding, which is measured by units of micro-deformation.

[2]Because of patent considerations, speeds on the order of 10 m/sec (for welding of ferrous metals) were considered initially in USA. According to new information, these speeds were lowered significantly (down to 2 - 2.5 m/sec.)

[3]One cannot call the fourth phase an upset, as it is done in electrical resistance welding, because during friction welding, the upset occurs during the entire process, including the heating, and is not a characteristic feature of one stage of the process.

[4]Sometimes, in particular during welding certain similar metals, the peening pressure may be equal to the pressure during heating ($p_{np} = p_n$).

[5]For materials and alloys sensitive to overheating, such a regime is undesirable. In these cases rigid regimes should be used. This, however, does not exclude the desire for increased pressures.

[6]For this, increased pressures are used.

[7]In large pressures the specified deformation is obtained in a lesser degree of metal plasticity, i.e. at lower temperatures.

[8]Because in this case, the upset occurs practically only at the expense of a more plastic metal, aluminum. Only part of the heat liberated in the butt, which is absorbed by aluminum is fed into equation (39). The relation of the heat distribution

during friction of two different metals is found from equation (40):

$$q_1/q_2 = \sqrt{c_1\lambda_1\gamma_1}/\sqrt{c_2\lambda_2\gamma_2} \tag{40}$$

[9]The dashes in this column signify that the welding was done without an upset die.

Chapter VI

FRICTION WELDING OF PARTS MADE FROM SIMILAR METALS

The friction welding of parts made from similar metals and alloys with the same cross section size, as a rule, is not very difficult. The conditions for success are: symmetry of the temperature field and the correct selection of the welding regime.

The first of these conditions is determined to a significant degree by the shape of the cross section for a length of 20 to 25 mm, then this guarantees for the duration of the process and the initial stage of cooling the symmetry of the temperature field relative to the butt plane. During this time, the heat cannot spread from the friction surface to the indicated distance. The shape and the size of the rest of the part (beyond the above indicated boundary) has practically no significance[1].

This condition was established during the study of steels and ferrous alloys (several dozen items), aluminum and its alloys, copper and its alloys, titanium and others.

The friction welding of almost all similar metals and alloys gives good results: the critical point, the bending angle, the viscosity, and other seam metal indicators are not worse than the indicators for the base metal. For hardening materials this, of course, occurs after corresponding thermal processing.

In a way of example, Fig. 36 presents welded solid samples which were bored after welding. The samples were subjected to testing for tension (the "neck" was formed far from the butt) and bending (without occurence of cracks).

Fig. 36. Samples of low carbon steel after testing for tension and bending (flash was removed). The arrows indicate the location of butts.

The characteristics of joints of several metals and alloys, which were produced by friction welding are listed in Table 4. The welding regimes of various pairs of similar metal and alloys are given in Table.2.

The necessary power for this can be determined from equation (26) and its specific value by equation (27). It should be remembered that the obtained values refer to the equivalent thermal energy consumed at the butt. To determine power consumed by the machine from the power line, the efficiency of the machine should be considered, which can oscillate between 0.8 and 0.5.

During calculation, when one is required to determine the power of the machine being designed for a specific cross section or, inversely, to determine the maximum cross section which can be welded on a given machine at welding regimes which were given in Table 2, the specific power for steel, for example, is on the order of 10-12 w/sq.mm. Considering the efficiency of the machine, the magnitude of power consumed from the power line per one unit of the initial cross section of the welding parts is on the order of 20 w/sq. mm.

When developing the friction welding technology of parts with continuous cross sections, it is necessary to specify, besides the process parameters, the length of the free end of the part (relative to the clamp). The end should not be very short to avoid the danger of contact of faces of the rotating and the stationary clamps (this can lead to breakdown, or, in any case to worse quality of the welded joint because the force of the machine will not be felt by the welding parts but directly by the clamps) and to prevent the clamps from heating up because of the close proximity of the butt. At the same time, the free end of the part should not be very long in order not to affect the part in its resistance to longitudinal bending.

The recommended optimum length l of the free end depending on the diameter d of the part lies between $0.5d < l < 1.5d$. The lower limit is preferable for small diameter parts and for parts made from more plastic materials. For steels with more than 15 mm diameter, l should be approximately equal to d.

Thus, the welding and preparation for welding of similar parts with the annular cross section is relatively simple.

The technology of welding and preparing parts for welding becomes more complicated when one goes to parts and joints with more complicated shape.

18. The Welding of Tubes and Parts with Tubular Cross Sections

The friction welding process for tubular parts of comparatively large cross section is basically identical to the welding process of parts with continuous cross section. However, when welding thin-wall tubular parts a series of difficulties usually arises. If continuous cross section parts are joined somewhat

off their co-axis this may not cause serious consequences. It can be easily corrected by consequent machining of the part (of course, if the eccentricity does not go beyond an allowable limit). For instance, if the co-axial alignment of the part is caused by incorrect orientation of machine clamps and is 0.5 mm (which is entirely possible), then during welding of a continuous rod with 20 mm or larger diameter there is no practical effect. However, if one tries on the same machine to weld a tube with a wall thickness, for instance, of 2 mm, then the displacement of the two cross sections by the same 2 mm is not permissible in most cases because the thickness of the wall will be reduced by 25 percent. Attempts to correct the axial alignment will lead to the change of the nominal size of the cross section and to a decrease in the wall thickness almost by a factor of two. It is possible that the welding of such tube cannot be achieved at all because during the relative rotation or during mutual compressing of tubes their walls may lose strength and crumple. This effect may be especially apparent if the welding is done under increased pressure during peening. Therefore, during welding of tubular parts, the requirement for co-axial alignment of the parts is increased. The thinner the wall of the welding part, the higher this requirement.

Because of the same reasons, the welding of thin-wall tubular parts is possible only for correct shape and size of the cross sections. The distortion of edges, the ellipticity of the cross section, the change in the wall thickness along the circumference, and the difference in the diameter of the tubes joined should be at a minimum. In opposite case, the deformation of the walls is unavoidable. As a result, crumpling of the tube walls will occur instead of their joining.

To preserve the shape of the circumference of the cross section of a tubular part it should not be clamped with the usual

type of clamps. It is necessary to undertake additional measures such as intermediate mounting, plugs installed inside or at the edge of the clamp, which envelop the tube almost along its entire circumference.

To insure strength in the walls of the tubular part, its free end should be at a minimum. This, especially, applies to parts made from materials with increased plasticity, for instance, aluminum and copper. The minimum length of the free end of the tube may be determined as the sum of complete upset (heating and peening), room for distribution of flash and some tolerance.

A majority of the above requirements and conditions do not apply to tubular joints with a wall thickness of more than 3 mm.

During welding of thin-wall tubes following steps can be recommended to prevent the indicated difficulties:

1. Short tubular parts with continuous smooth openings can be friction welded by installing inside the tube plugs from hard material (Fig. 37). Such a plug, if it is sufficiently tight, will prevent deformation of the cross section of the tube when the latter is clamped to the machine. The clamp, in this case, may have two or three jaws. This plug straightens out the tube if before welding it had elliptical cross-section or crumpled edges. Correctly selected (according to above notions) distance l between the end of the tube and the end of the plug contributes to increase of strength in the walls of the tube.

One can assure the minimum eccentricity (for very thin wall tubes) with the help of mutual alignment of such plugs, for example, as it is shown in Fig. 38. To decrease the wear of the annular finger of one plug and the corresponding opening in the other plug, the latter can have ball bearing.

Several sets of such plugs insure continuous operation of the welding machine. The outfitting of the next pair of parts to be welded with plugs takes place during welding of the previous pair.

2. If, because of production conditions, it is impossible to install plugs inside the parts, then they can be replaced by enveloping collars. The latter can be continuous or sectional. The continuous collars are installed between the clamp and the welding location. The sectional collars play the role of the chuck and permit the use of common jaws for clamping of tubes. In this case the collar is clamped by the jaws. As internal plugs, the collars permit the removal of ellipticity of the tube and an increase in the strength of its wall, if the free end (relative

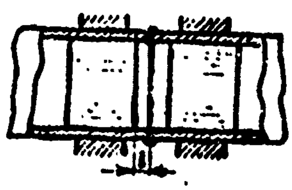


Fig.37. Welding of tubular parts with installed plugs.

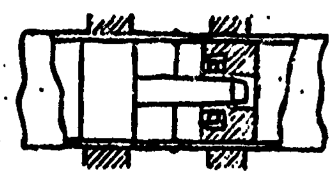


Fig.38. The mutual centering of tubular parts.

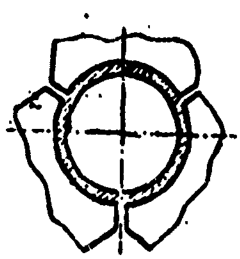


Fig.39 Clamping of tube from outside.

to collar) is sufficiently small. For thin-wall tubes, where hig. degree of axial alignment is required, one can design devices which are analogous to the device shown in Fig. B. The difference is that instead of the central finger one collar has several fingers with rollers, which envelop and at the same time

center the collar installed at the opposite part and roll along its surface.

3. Machines intended for welding of tubes are equipped with multijaw clamps, which permit the gripping of the tube almost along its entire circumference. Such clamps, Fig. A, should have not less than three jaws. This is dictated because of the convenience in centering the part and by the location of the jaw at the tube surface without damaging the tube outer surface.

19. Welding of T-Joints

In T-joints a rod or a tube is butt welded to a flat surface of another part. The basic feature of welding of such joints is the assymetry of the temperature field. From a flat source on the friction surface the heat is spread frontally along the axis of the rod in directions normal to certain spherical surface in the body of the other part. This difference in the intensity of heat removal from the friction surface causes assymetry of the temperature field. The temperature gradients are different. The wear process of the contacting parts flows differently. The temperature gradients are lower and the mechanical properties of the metal are worse in the rod than in the opposite body. One observes in the rod the depth extraction of metal particles. In the massive and less-heated opposite body the effect of surface polishing with minimum wear of metal in depth occurs.

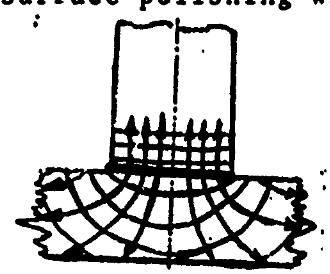


Fig.40. Temperature field in a T-joint.

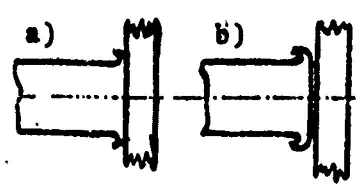


Fig.41. The scheme for the transfer of metal from the rod to the plate: a) beginning of the friction process, b) long heating time (cross-hatching indicates transferred metal).

The particles of metal extracted from the body of the rod are welded on to the surface of the opposite body. First, a thin layer of the metal transfered from the rod is formed. Then this layer gradually thickens. The "collar" (in this case one sided) gradually moves away from the flat surface of the part. Between the surface of the part and the end of the rod a column of "melt" is formed.[2] This metal, which underwent thermomechanical processing during friction has a fine grain structure (by microscopic analysis), is free from flaws and has high mechanical quality. The quality of the joint of built-up metal with the surface of the opposite body depends to a great degree on the initial conditions of the process. Most importantly, it depends on the perpendicularity of the flat surface of the massive part and the axis of rotation of the rod. If this condition is not met (because the flat part is hardly deformed) non-fusion on one side may occur. This lowers the strength of the joint when compared with the strength of the base metal.

Tests showed that to achieve good quality of joint the face wobble should not exceed 0.2 to 0.25 mm.

In the practice, cases are often encountered when T-joints of rod with a flat part made from low carbon steel react well in stress (even during direction variable dynamic load) but do not react well in bending. Sometimes, this meets the operational requirements for such a part.

When welding T-joints the speed and the pressure are selected from Table 2, as in cases of welding of symmetrical joints. The heating time and upset are best determined empirically. The heating process has to stop as soon as "peeling" of the collar from the flat surface of the part occurs. Sometimes, new formation in form of a small metal ring occurs between the collar and this surface. This is also an indicator for the end of the

heating.

The first edition of this book listed the relation $\delta_n = d/4$ connecting the diameter d and the thickness δ_n of the plate. It was assumed that only during this relation the joint will have optimum properties. The following experiment showed that the thickness of the part to which the rod (or tube) is welded has no effect on the quality of the joint. Only the minimum thickness of the part should be limited. It should not be easily heated in its entire depth. To lower this limiting thickness one can use backing from well conducting metal, for instance copper.

To assure high quality of T-joints following measures are recommended during welding:

1. Machine the surface of the flat part in the friction welding machine, then weld without changing the clamping;

2. reduce the problem of welding the asymmetric T-joints artificially to the problem of welding of a symmetric joint. To achieve this two ways are possible: a. provide for a projection (by casting, forging, or machining) on the surface of the flat part (Fig. 42,a), the diameter of this annular projection should be the same as the diameter of the rod to be welded on and the height should be 3-6 mm for steels and somewhat larger for plastic metals; b. or machine an annular groove at the face surface for welding of this part with the rod (Fig. 42,b); for welding with a tube the flat part is prepared as shown in Fig. 42,c.

The depth of the groove in both cases should be less than 3-5 mm for steel and somewhat larger for parts made from plastic metals. To obtain reliable (sealtight) joints of the tube with

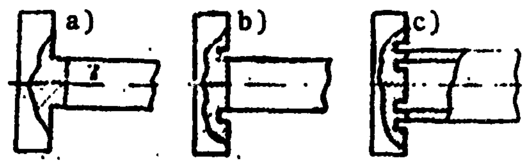


Fig. 42. Preparation of the flat part before welding of the T-joint of a plate with a rod (a and b) and the tube (c).

the flange it is recommended for this type of joint to follow the scheme shown in Fig. 42,c.

All indicated variations of preparation of parts for welding assure good quality of T-joints. The welding regime should be selected from table 2, as for symmetrical joints.

20. Welding of Parts with Different Size Cross Sections

This type of joining, when two annular rods of different cross section are joined, can be considered as a T-joint. All recommended methods of preparation for welding for T-joints can be used in this case. One can also recommend the machining of the larger diameter to the size of the smaller, i.e. to reduce the case of welding of different diameter parts to one of welding equal diameter parts. The depth of the machining should be 3-6 mm for steel and somewhat larger for aluminum, copper, and other plastic metals.

21. The Welding of Parts with Large Cross Sections

Each welding machine is designed for a completely determined range of cross section of welding parts. The upper limit is determined usually by the power of the machine and maximum magnitude

of force developed by the machine.

However, in practice, one often encounters the necessity to weld parts with larger cross section than the machine was designed for. In this case one can obtain completely satisfactory joints, if the butt surfaces of parts (of one or better of both) are prepared before welding. Fig. 43 presents one of the possible versions of such preparation, the machining of the peripheral part of the friction surface to cone shape. In this case, the maximum moment and power of friction (Fig. 21) will

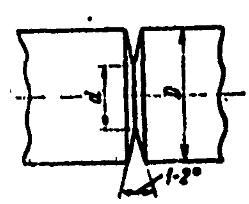


Fig. 43. Preparing the ends of large-diameter rods.

take place in the time when the diameter d and the friction surface area are comparatively small. As the upset of parts increases the friction surface increases. However, the magnitude of the unit power consumed decreases. As a result, the welding process occurs with relatively small consumption of power and energy. The welding process should be stopped after the friction surface reaches the nominal cross section of the part D. It is understood that the magnitude of upset in this case should be selected larger than for an ordinary case by the length of the recess. The time of heating will also be longer. The welding regime will be soft and the heating of the parts will be in depth (increased when compared with the ordinary process).

Another method of welding of parts with large cross sections using a relatively low power machine is the decrease in the cross section of the welding part by boring out its central part before welding. This version is less successful than the previous one because the cross section of the part is reduced at the butt.

One has to consider that there are gases in the enclosed space inside the joining parts. These gases are heated to high temperatures. The compression of the parts leads to a break out of these gases through the plastic metal and to formation of a crack in the butt. To avoid this undesirable phenomenon one of the parts has to have a drainage (bore a small diameter opening 1.5 to 2 mm).

22. How to Obtain "Flashless" Joints

In some cases, for instance during welding ferroconcrete parts, the flash (collar) remaining after welding is not only harmless but is very useful because it improves the grip of the steel rods with concrete.

As will be shown later (see chapter VII) the preservation of the flash is useful in parts intended for operation in corrosive environment. The flash is also not harmful in parts and machines operating at static loads if the presence of the flash does not go against esthetic requirements.

However, in majority of cases the flash should be removed.

The flash is not permissible, for instance, on parts under dynamic loads because its specific shape is favorable for local stress concentration in the area of the butt. The removal of the flash by machining is necessary for such parts.

There are a series of cases when the presence of the flash is undesirable because it occupies part of the space which was intended by the designer for other purpose. For instance, flash formed during friction welding of a prong to a flat surface prevents, if it is not removed, the placing of a washer close to the flat surface. Inside a tube the flash creates local resistance to flow of liquid or gas in the tube, etc.

In these cases, one can use some measures which will enable to hide the flash in "pockets" provided beforehand (Fig. 44). This method may be used, of course, only in those cases where the reduction in the cross section of the rod or tube is permitted by the operational conditions of the part.

Another method of obtaining almost flashless joint is based on preventing the flash formation during welding. This method is more applicable in welding of tubes than rods. The external flash of the tube butts is in many cases not an obstacle. However, if it has to be removed this can be accomplished relatively easily on the lathe. More complicated is the removal of the flash inside the tube, especially if it is long.

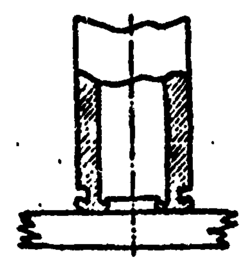


Fig. 44. The preparation of a rod (or tube) for hiding the flash within the initial diameter.

In this case one can prevent the flash with the help of a plug installed before welding (Fig. 45) in such a manner that the butt of the part is in the area of its conical surface. During the upset, the small gap formed between the plug and the internal wall of the tube prevents the spontaneous formation of the flash and forces the metal into this gap in the form of a thin "stocking". The internal diameter of the tube is almost unchanged after welding and the formed flash is

not a hindrance to the flow of liquid or gases in the tube.

The extrusion of metal from the butt may have a twofold asymmetrical character:

1. the flow of metal to the outside, not being curbed by anything, will be easier than inside the tube. Therefore, the degree of deformation of the metal at the external and the internal walls of the tube is different;

2. the metal flows into the gap between only one of the parts. The metal is not forced into the gap between the plug and the part whose rotation speed relative to the plug is zero.

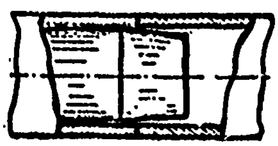


Fig. 45. The welding scheme of pipes with minimum formation of the flash inside the tube.

The asymmetry of the metal deformation leads to worse properties of the welded joint. However, in a series of cases it is not an obstacle to the use of this method.

The surface of the plug should be covered with an alloy of high hardness, for instance by stellite or sormite, to prevent its rapid wear and welding to the tube. Then, the surface is carefully processed. The conicity of the plug should be such that it should be removed conveniently from the tube. The gap between the cylindrical part of the plug and the walls of the tube opening should be 0.5-0.6 mm, the conicity of the other part of the body should be 1:15 or 1:10.

Using the same method one can limit the shape and the size of the external flash during welding of pipes or rods. Instead

of a plug the butt is placed inside a chuck placed on both of the welding parts and having a certain gap.

The method described, although it is used in the practice, can be recommended for limited use only because of the following deficiencies:

1. the surface of the plug wears out relatively fast, even with a build-up of a hard alloy, this requires frequently the repair or replacement of the plug;

2. with a small gap between the plug and the tube, especially when the tube is long, the removal of the plug after welding is difficult and laborious;

3. tubes with such enforced formation of flash have usually worse mechanical properties in the butt metal (because of the asymmetrical flow of the metal during upset);

4. butts of such tubes have lower corrosion resistance (the crevice corrosion in the gap between the body of the tube and thin-wall tubular body of the flash, the "stocking").

In cases when the flash of minimum size is allowed it is recommended (17) to friction weld at increased rotation speeds. However, this forces the use of preliminary precision machining of the faces of the welding parts.

It is not impossible that in the future the optimum solution of the problem of flashless welding will be solved as a result of combination of the friction welding with other types of welding.

23. Welding with Forced Formation of the Seam Metal

Very interesting results were obtained by P.M. Sutovskiy et al. (48) in their work devoted to welding of tubular joints.

In this work the authors showed, based on previously published studies that during deformation of butt metal under triaxial compression, the quality of the joint becomes better than during the usual scheme for friction welding, which is close to the scheme of uniaxial compression.

The conditions of the triaxial compression of the butt metal may be created by limiting the free efflux of metal in the radial direction. In particular, applicable to tubes, the simultaneous use of an internal plug and an external collar is proposed (Fig. 46). Therefore, the proposed scheme is close to the considered above cases of limiting the flash formation. However, it is basically different from them because there is no deformation asymmetry along the cross section of the tube. The flow of metal is made difficult to the inside as well as to the outside. There is no basis for impairment of metal properties. In addition, it was shown in reference (48) that the properties of the butt metal are higher than during uniaxial compression. The mechanism of this phenomenon, apparently, is close to the one described above. The creation of the artificial barrier, which prevents the metal from flowing in the friction surface and which creates the condition for triaxial compression subjects all volumes of the surface regions of the butt metal (independent of their distance from rotation axis) to almost equal conditions of deformation.

It is necessary to note, however, it is completely inadmissible to completely "close" the butt metal and to "forbid" its

flow in radial direction (even if it was practically possible). To obtain high quality welding joints, the plastic deformation of the welding parts in the butt plane is necessary. The necessity of such deformation (of a certain minimum magnitude) is connected with the necessity of assuring an escape of dislocations to the surfaces and the formation at the surface of active nodes (seizing nodes) and also with the removal from the butt of oxide films and contaminations.

In the mentioned work (48) its authors propose, for obtaining even better quality welded joints using the method of "forced deformation", to give the ends of the tube a conical shape so that the butt will become slanted in the cross section. Such a shape of the butt makes it possible to improve the operation of the joint when stress forces torsion and bending moments, and their simultaneous action are applied.

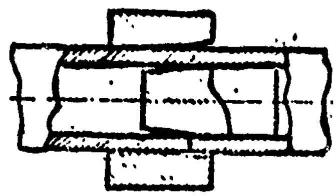


Fig. 46. The scheme for welding of tubes with biaxial forced formation of flash.

24. The Oriented Joining of Parts

Often, in practice, it is necessary to join the parts in such a manner that after welding they are oriented in a certain way with respect to each other. This is necessary, for instance, if both parts have drilled openings, whose axis should be parallel and in some other cases.

During the ordinary friction welding it is impossible to guarantee such an orientation. One of the parts rotating around its axis stops after the end of braking in an arbitrary position

(with an arbitrary angle of rotation) relative to the other, stationary part. Because of the small length of the braking path (in contemporary friction welding machines it is about 0.5 of the revolution of shaft and short time of "coasting", several tenths of milliseconds, it is practically impossible to control such a braking process. Many proposals made to remove this difficulty are unrealizable either because of the unworkable devices proposed or because of tremendous complexity and small reliability.

Up to now, the only completely real and simple method for friction welding of two mutually oriented parts is the process whose scheme is shown in Fig. 6,a. According to this scheme two welding non-rotating parts can be aligned one relative to the other to any precision and then welded together with the help of a third rotating body compressed between them. Several machines were already built for this scheme.

In this scheme, the central part of the piece (third body) has to have an annular or nearly annular continuous or tubular cross section.

The inconvenience of this scheme is the complexity in the design solution of the holding point and the simultaneous rotation of the middle part (third body) of the piece.

However, there are already a series of successful design solutions to this problem. In one of the foreign patents (78) the idea of welding of two stationary parts with the help of rotation of a third body compressed between them applicable to tubes is realized in the following manner (Fig. 47): the ends of the two welding tubes 1 and 2 are placed on the shoulders of the intermediate part 3 as shown. The part 3 is brought to

rotation by a rod placed in it which was earlier connected to part 3 by means of a groove or a cotter. The intermediate part remains in the joint.

Because of the narrowing of the tube in the butt zone, which, as a rule, is inadmissible, the proposed solution can be successfully used only during welding of tubes, which operate as load carrying structural members.

In this case, the proposed solution, apparently, is successful not only in rotation of the center part and because of achieved coaxiality of the welding elements, but also because of good behavior of the joints under stress and bending loads.

It should be noted that many attempts were made to use the scheme of friction welding with a rotating third body without the body remaining in the butt. Some authors proposed, for instance, to heat the butt by a rotating disc with a large diameter with the axis of rotation beyond the limits of the welding parts. To obtain the required plasticity of the ends of these parts the disc is quickly removed from the gap between the two parts. Then, the latter are brought together, compressed and a welded joint is formed.

This method has a basic flaw: it is impossible to obtain a satisfactory joint. The rotating disc is cooled and oxidized. A part of these oxides remains in the butt. When the disc is removed from the butt, no matter how short the required time span is, the friction surfaces are oxidized and cooled.

This scheme had no success.

25. The Joining of Unusual Shapes

The friction welding (by rotation) of parts with non-annular cross section is basically possible but with some limitations. For instance, one can butt weld two rods with square cross section (without a third body). The joint is of satisfactory quality but only along the presented periphery (Fig. 48). The cross-hatched areas are exposed, oxidized, and cooled during ro ation. Therefore, e en during matching of the cross sections the joint in these places is of lower quality. Therefore, one cannot count on loading the corners of the cross section if at the end of welding the cross sections do not match.

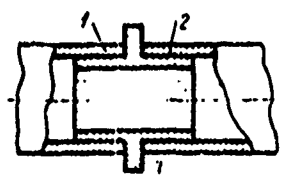


Fig. 47. The welding of two stationary tubes with the third rotational body: 1, 2 welding tubes; 3 grooved intermediate part.

During butt welding of two rods with hexagonal cross section with formation of relatively large collar the joining is almost along the described periphery because the metal forced into the flash tends to assume the annular shape. The friction

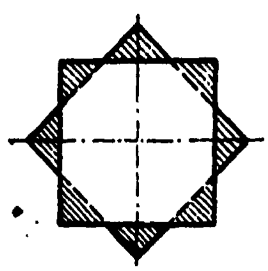


Fig. 48. The instant of exposure of peripheral portions of the cross section during welding of two specimens having a square cross section.

Fig. 49. T-joint of annular rods.

surface takes an annular shape. There are no protruding corners which can be oxidized. The area of the joint may be calculated assuming the entire area of the hexagonal cross section. Of interest is the following: if the process is not continued to abundant flash formation, the joints are formed with almost precise matching of corners and faces of both hexagons. This can be explained by the fact that during rotation the magnitude of the friction surface is not constant. It reaches a maximum during matching of corners and decreases when the corners move away from each other. In connection with this, the friction moment changes also. During coasting, the final stop occurs when the friction moment reaches a maximum (in this case it should be considered as a component of the braking moment), i.e. when the corners of the hexagonal coincide. This effect is more pronounced when larger part of the useful friction moment (in the butt) is common with braking moment.

In one of the electrotechnical plants, the T-joint welding is successfully accomplished for non-essential part (parts which do not carry large loads). The parts are made from two sheet stampings. A plate, which has a rectangular friction surface with the 1:2 proportion of the sides, serves as the rod. High quality welding is only obtained in the central part of the cross section of such a shape. The strength of the joint is completely satisfactory.

We conducted preliminary experiments in welding of T-joints of two annular bars with the same diameter (Fig. 49).

Just as in previous case the joining is not along the entire cross section. As a result of deformation of both parts, the friction surface assumes complicated form close to an ellipse. Within this surface the strength of the joint is completely satisfactory.

Footnotes to chapter VI:

[1]They only influence the selection of the design and the size of the clamps of the machine.

[2]The term "melt" is in quotes only because the process takes place without melting of metal.

Chapter VII

THE FRICTION WELDING OF PARTS MADE FROM DIFFERENT METALS AND ALLOYS

The advantages of friction welding, which were considered in chapter I, permit welding an overwhelming number of combinations of dissimilar metals and alloys including those which cannot be welded or are very difficult to weld using other types of welding. Table 3 lists welding regimes of some combinations of dissimilar metals and alloys. Table 4 presents the characteristics of the joints. Only a few of the combinations tested (Table 1) could not be friction welded.

A successful completion of high quality joints often requires the use of special methods.

It was indicated above that common plastic deformation of metal surface layers of the welding parts is one of the basic conditions for obtaining a reliable joint.

It is apparent from the examples cited for welding of similar materials that even a simple infraction in the geometrical shape of parts (relative to the butt plane) leads to the asymmetry of the deformation and, as a consequence, to worsening of the properties of the welded joint. Besides the different geometry of parts close to the butt, there are other causes for asymmetry of deformation: different intensity of heat removal from the contact surface along both sides because of the difference in thermophysical properties of the welding metals, difference in temperature gradients and mechanical properties of these metals, asymmetry of the temperature field.

Besides, during welding of dissimilar metals (alloys) the strength and other mechanical properties of the joint depend to a large degree on the mutual conformity of the types and parameters of the crystal grid of the welding materials, their chemical interaction, synchronization of the ejection of dislocations to the contact surface during the common deformation, equal or close values of the temperature coefficients of linear expansion, and others. Of great significance are the diffusion processes dur ng the common deformation, equal or close values of the temperature coefficients of linear expansion, and others. Of great significance are the diffusion processes during welding and during consequent repeated heating of the joint. They contribute to a quicker growth of the actual contact area after formation of seizing contacts between the contacting surfaces. However, one cannot consider diffusion as a process, which determines the formation of the welding joint. This is a secondary process, which in many cases contributes to the welding process[1] and accelerates the welding.

All these factors are hardly reflected in the formation of the welded joint and its quality if the physical and chemical properties are close for a given pair of materials. If materials with sharply different thermophysical and chemical properties are welded it is very hard to obtain high quality joints.

Significant practical experience in friction welding of complicated combinations of materials has been already accumulated.

We will consider more interesting and important data below.

26. The Welding of High-Speed Steel with Structural Steel

The end cutting tool (drills, end cutters, taps, reamers) should be made from different steels. The cutting (operating) part should be made from expensive and rare steel (R9, R18, RK 5, RK 10, etc.) which has high wear resistance, hardness, and red hardness. For manufacturing of the rest of the tool, one usually uses structural steel (45, 40KH, et al) because of higher viscosity and economic considerations.

Earlier, the joining of the tail section was done with the help of electrical resistance welding.

The friction welding began to replace resistance welding in the production of the cutting tools several years ago. It is being introduced in the mass production plants specializing in tools as well as in limited production plants of large metal processing enterprises.

At the present time, the friction welding was already adopted by a series of specialized plants: Vilnius Drill Plant, Moscow, Chelyabinsk, Tashkent, Orenburg, Sestroretsk Tool Plant, Moscow plant "Frezer", and also in the tool plants of such large enterprises as Gor'kiy Automobile Plant and Moscow Likhachev Automobile Plant, Altay and Chelyabinsk Tractor Plants, et al. More than half of the operating Soviet friction welding equipment is used in the production of cutting tools.

The friction welding is extensively used in cutting tool production in Poland. There is great interest in this technology in the German Democratic Republic and other countries.

This is explained by the technical expediency of substituting

the resistance welding by the friction welding and the large economic advantages in doing so.

During friction welding, the quality of the joint is improved and the stability of its properties is significantly increased. Savings in the rare high-speed steel are achieved. The consumption of the structural steel is lowered. The power for the equipment is decreased. Cos ϕ is improved.

In addition, the welding defects are reduced by 5 to 15% (depending on the character and conditions of production in a given plant) and the productivity is increased.

Careful studies of friction welding of a large batch of cutting tools performed under industrial conditions were performed at the Voskov Plant (1). They confirmed convincingly the data on increase in the stability of the welding quality and the reliability of the tools when the resistance welding was substituted by friction welding (table 5).

Besides statistical tests, studies were conducted in the fatigue of the welded joint. Based on 10^7 cycles the fatigue strength of the joint made from steel R18 + steel 45 was 21-22 kg/sq. mm for samples which were friction welded as well as for samples which were welded using the electrical resistance welding. It should be noted that the latter samples were welded in the laboratory and the former in an industrial plant.

Reference (1) presents results of tests of the friction welded tools (cutters, drills) under their normal operational conditions but under loads which significantly surpass the standard. Keyway cutters were supplied to the machine at 4 times the normal rate and the machine rotated at twice the normal

Properties of Joints Obtained by Friction and Electric Butt Welding

Table 5

Material Tested	Diameter of the sample in mm	Type of Welding	Stress Tests: σ_v in kg/mm²	Stress Tests: σ_t in kg/mm²	Bending Tests: σ_{izg} in kg/mm²	Torsion Tests: τ_{kr} in kg/mm²	Torsion Tests: Torsion angle in degrees	Remarks
Steel R18 + Steel 45	10	Electric Butt	58—62	36—38	—	44—45	250—500	Machined Samples
		Friction	58—62	38	—	56—60	325—500	
Steel R18 + Steel 45	15	Electric Butt	45—61	31	—	—	—	Machined Samples
		Friction	47—60	30	—	—	—	
Steel R18 + Steel 45	12	Electric Butt	40—58	38	110—120	58—61	400	Raw Samples
		Friction	48—56	38	—	58—62	400	
Steel R18 + Steel 45	18	Electric Butt	41—52	29	70—105	—	—	Raw Samples
		Friction	39—50	29	70—100	—	—	
Steel R18	—	—	85	41	132	76	—	Mechanical properties of initial materials given for comparison
Steel 45	—	—	64	30	105	82	—	

Notes:
1. Table presents minimum and maximum values obtained during testing.
2. Table was taken from reference (1).

Various Welding Regimes for Cutting Tools Made From Steels R18 and 45 Using a Die

Table 6

Diameter of the peice in mm	Speed of relative motion: [illegible]	Speed of relative motion: [illegible]	Unit pressure in kg/mm²: [illegible]	Unit pressure in kg/mm²: [illegible]	Heating time in seconds	Total upset in mm	Bibliographical Source
20	1000	1,0	8	16	11	2,5	V.I. Vill' (13)
30	1000	1,5	7—8	15	18	3,0	
10—22	1900—2100	1,0—2,3	8—12	18—22	2—8	3—4	Bakshi et al (4)
10—18	1500	0,75—1,4	9	15	5—9	2,5	I.V. Averin & N.N. Kabanov (1)
18—30	1500	1,4—2,3	9	15	10—12	3,5	
6—14	800	0,23—0,6	10—13	10—18	—	2—3	A.I. Khristoforov (51)
14	1200	0,85	13	13	—	3	
20	1450	1,5	12	16	10	4	R. Michal'ski (43, 74)
20	1450	1,5	16	16	10	5	

speed. The end cutters were supplied at a rate 5-7 times the normal rate again at twice the normal rotating speed. All cutters met the test requirements. Breaking of the cutting section was observed, but there was not a single destruction of the welded joint.

Reference (1) also presents a series of results of torsion tests for drills. It was established that the friction welded tool withstands a moment which is seven times higher than the moment necessary for drilling of steel with the strength limit equal to 75 kg/sq. mm during standard cutting regimes.

The high strength characteristics of the joints completely agree with the results of the study of their macro- and microstructures. In the friction welded joints made from steels R18 and 45 there is no ledeburite structure in the butt characteristic of electrical resistance welding. Instead, a badly stained band of fine grain austenite was discovered before annealing. The formation of the fine grain, apparently, is due to high rates of cooling of the butt and the small time period during which the metal is at high temperatures. The authors of reference (1) connect the presence of the austenite interlayer with the fact that the welding occurs in the temperature interval between points Ac_3 and melting.

There is less decarbonation of the structural steel and carbide impoverishment of the high-speed steel during friction welding than during electrical welding.

A smooth transition from the butt metal to base metal is formed in the thermal effect zone.

The favorable butt metal and thermal effect zone structure

are combined with the absence of macro-flaws of the joint in tools produced with the help of friction welding. When welding regimes are correctly selected there are no pores, cavities, oxide additives, stratification, cracks and other flaws in the butt.

The selection of the correct welding regime has a large influence on the quality of the welded joint. However, the experience in applying friction welding in cutting tool production showed that some variation in the welding regimes is permitted. Thus, the friction welding of a tool was performed by us first with a linear speed at the surfaces of the samples at 1 m/sec and during constant pressure cycle of 12 to 14 kg/sq. mm. Analogous friction welding regimes are successfully used (after 10 years) by many enterprises.

Later, the step pressure cycle with increased peening pressure was proposed, which is the base of many contemporary friction welding machines for welding of cutting tools, including special automats and semi-automats of type MSTA-31 and MF-327 (Chapter IX)

One of the research organizations recommended (4) a significantly more rigid friction welding regime for tools made from steels R18 and 45. The pressures for heating and peening are respectively 8-12 and 18-22 kg/sq. mm. An increased linear speed of rotation was recommended on the order of 1-2.5 m/sec.

On the other hand, several enterprises successfully introduced the friction welding of the same materials, recommended recently by other researchers (51, 52), which again used constant but increased (up to 16 kg/sq. mm) pressure. Then, it is possible to weld at decreased speed of 0.25 to 0.6 m/sec.

Finally, friction welding regimes developed in Poland (43) for steels which in their thermophysical properties are close to Soviet steels are different from regimes mentioned above. For convenience, the regimes mentioned are listed in Table 6.

All these regimes make it possible to obtain very satisfactory, in their mechanical properties, welded cutting tools. It again confirms the possibility of variation of the friction welding regime, in particular the rotation speed variation. This makes it possible to specify the friction welding regimes not only based on the process technology but considering other factors, for instance, the design of the machine, the production conditions at the given plant, etc.

However, in connection with the discussion above, it should be emphasized once more that it is inadmissible to vary only one process parameter. For instance, the change in the rotation speed makes it necessary to change the heating unit pressure or the heating time during welding.

The correct selection of the thermal processing regime after welding has also a great influence on the quality of the joint.

The joining of steel with different thermophysical properties may lead to appearance of internal thermal stresses. The plastic deformation of the supercooled austenite prevents the growth of these stresses to inadmissible limits. The appearance of cracks should be expected only after the beginning of martensite conversion in the butt region. During slow cooling of welded pieces from the temperatures of the order of 400 degrees C, the entire metal volume at each instant of time is heated to the same temperature. The martensite is formed at the same

time along the entire cross section of the piece. This prevents the crack formation. Therefore, the piece should be placed immediately after welding in a container with the above indicated temperature for consequent cooling of the entire container when it is filled with pieces. The more massive the pieces, the slower should be the cooling. This thermal regime is used in the overwhelming majority of plants for preventing of cracks after welding.

But even at such slowed down cooling process, the butt zone is of increased hardness. It is recommended to anneal the pieces before flash removal and mechanical processing according to one of the following regimes:

normal annealing (of previously cooled piece): heating during 8-10 hours to 850 degrees C, maintaining the piece at this temperature for 2 hours and slow cooling in the furnace to 500 degrees C for 10-12 hours, after this - cooling in air;

isothermic annealing: the pieces, without going into the container are placed into heated furnace which is slowly (3 hours) heated to 850 degrees C, then the piece is maintained at this temperature for 2 hours followed by step cooling to 740-750 degrees C for 4-5 hours maintaining at this temperature for 5-6 hours and further cooling (in furnace or in the container).

After mechanical processing, the welded pieces are subjected to quenching and three-stage tempering:

quenching - preliminary heating to 800-850 degrees C in barium chloride and common salt pool; final heating to 1260-1270 degrees C in salt barium chloride pool; cooling to 400-500 degrees C in melted caustic soda;

three-stage tempering in saltpeter pool at 550 to 560 degrees C for one hour.

The thermal processing regimes presented were borrowed from the Voskov Tool Plant. It is possible to use other regimes.

The experience gained during friction welding of cutting tools shows that using incorrect methods in preparation and welding following defects may occur in the welded pieces: annular non-fusion along the periphery of the butt cross section, non-fusion of the central part of the cross section and non-fusion on one side.

The cause for the annular non-fusion was shown in Chapter V (Fig. 28). It was pointed out that one of the methods to prevent the non-fusion is prolonging the process until the collar is of sufficiently large size.

Another method to prevent the non-fusion is to use pieces from more plastic metal (structural steel) with a diameter which is larger than the diameter of high-speed steel piece.

The excess volume of the cold metal because of the difference in diameters has the same influence in preventing the non-fusion as flash (Fig. 28). The desired effect is achieved with relatively small difference in diameters on the order of 15-20%.

However, this method of preventing non-fusion can only be recommended for small tool production volume, because additional consumption of structural steel is required and, more important, the consumption of labor grows. This is due to the necessity of using working time for the consequent machining of the piece to nominal diameter. It is more expedient to prevent the annular non-fusion by using the so-called upset die. Upset die is a ring into which the end of the piece from structural steel is inserted (in more general case: piece from more plastic metal)

as is shown in Fig. 50. This method is used at present time in almost all cases of friction welding of materials with different plasticity. The piece is installed in such a manner that the free end of the piece is at a distance a from the die. Between the body of the piece and the walls of the opening of the die there is a gap Δ. The die should have a chamfer b x 45 degrees. The volume of the chamfer is filled with metal of the free end of the deforming part during welding. The other piece made from high-speed steel is deformed only slightly at welding temperatures in axial as well as radial direction. The optimum size of the die should be selected experimentally. For orientation, one can recommend b to be from 1.5 mm for small diameter welding parts up to 3 mm for large diameter welding parts.

The gap 2Δ between the walls of the die opening and the surface of the welding piece is usually 1-1.5 mm. To prevent fast heating of the die following outside dimensions are recommended:

$$D \approx 5d;\ B - (0,8-1,0)\,d. \tag{41}$$

Usually a very rapid cooling of the die should be prevented because, as a result of the removal of heat by the cooled die from the welding piece, the quality of the joint may suffer. Usually, the dies are made from 5KHNT and other steels. Their life span consists of several thousand weldings. To increase the life span of the dies it is recommended to cool them periodically. In some machines (Chapter IX) water (MSTA-31) or air (Ta-10) is used for artificial cooling of the die.

The length a of the free end of the piece should be selected (6) by calculating the amount of the deformed metal that will

fill the chamfer. However, considering that the metal during welding flows beyond the limit of the chamfer, the actual magnitude of a should 1.5 to 2 times higher than the calculated.

In any case one should attempt to assure that the butt after the end of welding be in the plain of the forward wall of the die (Fig. 50). Usually, depending on the diameter of the piece, the overhang a = 1.5 to 5 mm.

Compared with welding without the die (see below) the upset of the structural steel is significantly lowered. In connection with this, the magnitude of the full heating upset and total upset is also decreased. Therefore, it is recommended to regulate the heating process during welding in the die not as a function of upset but as a function of time.

Non-fusion in the central part of the cross section occurs in those cases when the heat liberation during welding was insufficient because of the low power or short heating period. The characteristic sign of such a defect is the visible (by eye) area with a diameter of several milimeters at the fracture of the sample subjected to bending (without thermal processing). There are no traces of seizing at this area. This defect can also occur with insufficient peening pressure.

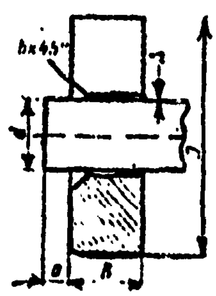


Fig. 50. Upset die.

One side non-fusion is usually connected with wrong

preparation of the piece made from poorly deforming high-speed steel before welding. When its face is slanted (Fig. 51) one can expect non-fusion in the initial gap between parts. To have satisfactory joint quality, the face of the high-speed steel piece should be normal to its axis. The deviation should not exceed several tens of a millimeter.

A smooth face surface of the high-speed steel piece which is normal to its axis can be achieved by machining the surface with polishing discs or by cutting with special differential stamps.

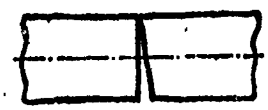


Fig. 51. The incorrect shape of the face of the piece made from poorly deforming material.

The requirement of the perpendicularity of the piece to its axis does not apply to the structural steel piece because it is easily deformed and the roughness of its surface disappears quickly during welding.

The observation of the indicated rules and regimes of welding and thermal processing practically guarrantees high and stable qualities of the tool which was friction welded.

The experience in friction welding accumulated in our country and abroad indicates not only technical advantages of the friction welding but also significant economic advantages when compared with electrical resistance welding. 1The friction welding makes it possible to significantly reduce the consumption of high-speed steel during butt welding of tools. In the electric welding, the contraction of the pieces is mainly at the expense of the burning out of the high-speed steel. At the same time, but to a lesser degree, a burn out of the structural

steel occurs also. During friction welding the high-speed steel is hardly contracted. The loss of the structural steel, especially when the die is used, is also lowered. Comparative data, which were obtained experimentally (1) are listed in Table 7. It is apparent from this table that in the diameter range of 10-30 mm the use of the friction welding makes it possible to save 2.5-3 mm of high-speed steel for each welding pair. If one relates this to the average cross section (22.5 mm) for diameter range indicated than more than 10 g are saved for each high-speed steel piece. A machine working two shifts with an average productivity of 80 welding per hour (theoretical productivity of such a machine is 110-120 weldings per hour) will save more than 4 tons of the high-speed steel annually. Money savings, using the USSR prices, amount to 20,000 rubles per year.

It should be added that the equipment for friction welding permits production of pieces welded with better axial alignment compared with resistance welding. This makes it possible to shorten the allowance for diameter processing and, as a result, additional savings of the rare steel and money are achieved.

The reduction of the electric power needed for welding, the improvement in cos ϕ, the reduction of the power of the equipment, the reduction of the necessary working areas, the decrease in the welding defects are other factors that make the economic effect of substitution of resistance welding by friction welding in the cutting tool industry more pronounced.

The improved properties of the welded joint and high economic efficiency which permit the recovery of expenses connected with the introduction of the friction welding within several months after the operation of the equipment explain the successful application of the friction welding in the metal cutting

Allowances for Electric Butt Welding (in mm) Table 7

Diameter of welded stock	Friction Welding			Electric Butt Welding		
	a	b	c	a	b	c
10—18	1	1,5	1,5	4	2	1,5
18—30	1,5	2	1,5	4	3	1,5

Notes:
a. Upsetting for preheating high-speed cutting steel stock.
b. Upsetting for preheating construction steel stock.
c. Machining allowance.
Table was taken from reference (1).

At present time, new cobalt-containing high-speed steels with increased hardness are being introduced. The friction welding of this steel, as preliminary studies indicate, is also possible.

However, for these steels special welding regimes are necessary. Technical investigations being conducted now are devoted to the development of these regimes.

Footnotes to Chapter VII:

[1]The diffusion may lead to embrittlement of the forming or already formed welded joint as a result of a brittle interlayer in the butt if the welding metals from chemical links between each other.

27. The Welding of Austenite Steels with Steels of Perlite Class

One of the most important tasks of the Soviet economy is to supply turbocompressors for diesel engines. The turbocompressors make it possible to increase the power per unit by 50-70%.

Up to now, the solution of this problem was made difficult because of the complications during the manufacturing of the turbocompressor rotor. The rotor wheel is made from austenite steels (alloys) because of the operating conditions (high temperatures - up to 700 degrees C) and the shaft is made from perlite steel. The joining of the shaft and the wheel by mechanical means is practically impossible because the mechanical joint does not assure the required precision in the balancing of the rotor. This is very important at 20,000-30,000 RPM.

The parts were usually lock joined after being provided with special chamfering. Then, they were welded using electric arc welding with an austenite electrode using several passes. After each pass, the seam was cleaned. The parts were heated before welding to 220-250 degrees C. If one considers that the diameter of the parts to be joined at the place of welding is not more than 60 mm and that 10-12 minutes are needed by a highly qualified welder to complete the joint, it becomes clear that this method cannot be used in mass production.

Preliminary studies of welding by friction of austenite steels (alloys) of various types with perlite steel yielded encouraging results. Based on these results, VNIIESO (Scientific Research Institute of Welding Equipment) together with NAMI (Automobile and Automobile Engine Research Institute and later with TSNIDI (Central Scientific Research Diesel Institute) and

other interested enterprises (Chelyabinsk Tractor Plant, Sverdlovsk Turbomotor plant, Yaroslavl Motor Plant) studied the technology of friction welding of 8 material combinations applicable to the industrial production of rotors.

As a result of this study (7, 8, 39, 62) it was established that the use of friction welding assures higher quality and, even more important, more uniform characteristics of the joints than for arc welding. A complete absence of distortion in the part was also established. Distortion was one of the big disadvantages of the old technology. The machine time during friction welding varies, depending on the size of the cross section of the welding parts and the combination of materials used for the wheel and the shaft, from 12 to 35 seconds. A complete welding cycle takes 1-1.5 minutes, approximately 10 times less than during the arc welding. Another very important advantage of the friction welding of these parts, as compared with the arc welding, is the facility for automation.

The purpose of further studies was to establish most favorable welding regimes for friction welding of cast high-alloyed austenitic alloys with the structural (perlite) deforming steels. The criteria for evaluation of the quality of joints were the strength characteristic of the joints, their stability and durability (reliability) under operational conditions at high temperatures (up to 400 degrees C).

A comparatively large number of combinations of materials were welded during the study. This was due to the fact that a parallel study was conducted on the selection of the optimum alloy for the rotor wheel.

The difficulty in welding of the austenitic alloys with

Table 8

Welding Regimes of Austenite Steel (Alloy) with Perlite

Welding Materials Diameter of rod in mm.	Parameters of Welding Samples: Unit Pressure in kg/mm² — Heating	Peening	Heating time in sec.	Rotation speed in rpm.	Total Upset in mm.	Sample protrusions in mm.
AVN-300 + EI415, Ø20	11	22	35	1000	3–4	2,5
EI572 + 40Kh, Ø20	6	21	9	1000	1,8	1,5
EI572 + 0KhM, Ø28	6	21	14	1000	2,2	3,0
EI696ML + 40G, Ø20	6	21	12[1]	1000	3,0-3,5	2-3
EI787L + 40G, Ø20	6	21	12	1000	3,0-3,5	2–3
EI787L + 40Kh, Ø20	6	21	12	1000	3,0–3,5	2–3
EI893L + 40G, Ø20	6	21	12	1000	3,0–3,5	2–3
EI893L + 40KhS, Ø20	6	21	12	1000	3,0–3,5	2–3

1. During welding of rods with indicated composition with large diameters the hearing time increases. Thus, for welding of rods with a diameter of 36 mm, the heating time is 25 sec.

the perlite steels is due to the difference of the many thermophysical properties, in particular, in the linear expansion coefficient. Besides, the joint may be brittle because of formation of a transition structure in the joint. Finally, during welding of the austenite steels with perlite steels a tendency to crack formation is observed during sudden repeated thermal cycling.

These features of the welding of these steels are characteristic, to a large degree, of the electric resistance arc welding.

The absence of melting of metal and the short time at which the metal is at a high temperature during the welding process

significantly alleviates the obtaining of reliable joints during friction welding. However, careful selection of the welding regime is necessary for friction welding just as for arc welding.

The different degree of plasticity of perlite and austenite steels forced the use of an upset die (just as in the case of welding of cutting tools using friction) during friction welding. The die was installed at a shaft from perlite steel.

Step pressure cycle was used. The usual ration of peening pressure to heating pressure equal to two was insufficient. The absence of the stability in the bending angle and viscosity, as well as the brittleness of joints, make it necessary to increase sharply the peening pressure to force, from the butt, metal with intermediate structure, thus achieving the required values of the parameters. The studies of the microstructure of the butt metal established that the application of significant peening forces (pressures) leads to a decrease in the thickness of interlayers with low mechanical properties of intermediate structure, which has a negative effect on the characteristics of the welded joint.

Table 8 lists regimes which assure a high and uniform quality of the welded joints.

Samples of joints welded during these regimes were tested under static loading and also for viscosity. The indicators were high (Table 9). In addition, they were tested for fatigue strength (Fig. 52). As in testing for stress, the samples are destroyed far from the butt and the thermal effect zone at the base metal (austenite steel) during fatigue testing. This is explained by some strengthening of the butt metal and increase

Properties of Austenite-Perlite Steel Friction Welding Joints

Type of Welding Steel and Alloys	Testing Temperature in degrees C.	Tension Testing σ_e kg/mm²	Tension Testing $\sigma_{0.2}$ kg/mm²	ψ in %	Destructive Torsion Moment M_{kr} in kg.m	Viscosity α_n in kg/cm²
ANB-300 + EI415	20	79—90	[1]	[1]	—	2,3—3,1
	450	77—79	75	18,7	—	2,5—1,0
EI572 + 40Kh	20	62—66	34—37	1[illegible]—20	162—167	3,85—6,25
	400	50—57	25—30	1[illegible]—23	110—120	3,75—4,75
EI572 + 0KhM	20	66	37—41	5[illegible]—60	150—153	4,75—6,0
	400	51—59	25—28	4[illegible]—59	117	4,0—5,75
EI696ML + 40G	20	60—64	43—46	20—22,3	—	3,4—5,0
	400	53—45,8	45—40,6	1[illegible]—13	—	3,3—3,0
EI787L + 40G	20	70—77	54—48	16—14	—	4,0—6,1
	400	63—66	43—58	17	—	3,3—5,2
EI787 + 40Kh	20	71—76	48—51	17—18,3	—	3,0—4,7
	400	62—65	46,5—44,7	13,0	—	3,1—4,5
EI893L + 40G	20	60—68,6	44,5—48	5,1—6,4	—	5,4—7,0
	400	48—51,8	45,4—51,8	7,0—8,1	—	8,0
EI893L + 40KhS	20	50—53,6	30,5—33,4	37—12,8	—	4,0—7,1
	400	51—51,6	23,4—22,0	22—42,1	—	4,1—7,0

1. Because of high brittleness of nickel alloys, where fracture took place, it was impossible to determine the relative deformation critical yield.

in the butt metal hardness as a result of upset cold hardening, which is not completely removed because of the short period of the thermal cycle. For comparison, samples welded with arc welding were tested for fatigue strength under analogous conditions. Their fatigue strength was significantly lower and the destruction took place along the butt (if the fatigue strength of friction welded samples was 26 kg/sq. mm at normal temperature and 20 kg/sq. mm at 400 degrees C, then the fatigue strength of arc welded samples was 20 and 14 kg/sq. mm respectively).

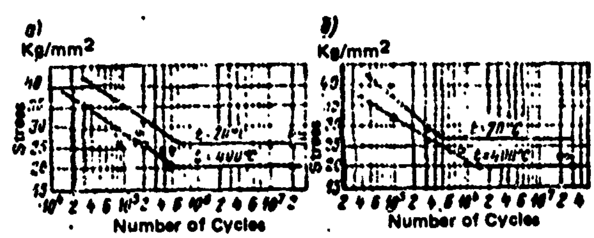


Fig. 52. Results of fatigue strength testing (7):
a - EI572 + 40KH; b - EI572 + OKHM.

The torsion testing of the samples established (7), as was to be expected, that not only the welding regime but also the regime of the consequent thermal processing has an effect on the strength of the joint.

The instability of structure and mechanical properties a along the length of the seam is decreased with the help of thermal processing. The same work (7) concludes that completely sufficient, for practical purposes, criteria of the joint strength of the austenite with perlite steels are the magnitude of the viscosity and the destructive torsion moment.

At present time, the plants mentioned above, successfully incorporated the friction welding of rotors TKR-10, TKR-12, and TKR-18 with diameters welding of up to 60 mm.

28. Welding of Aluminum with Steel

The need of the contemporary technology for permanent connection of the aluminum and its alloys with different types of steel is tremendous (2). But until recently there were no methods to achieve these joints. The cold welding of steel with aluminum is completely impossible. The welding of steel with aluminum at raised temperatures is accompanied by reactive diffusion, i.e. by such diffusion process as a result of which chemical compounds of the components are formed. Aluminum with iron forms a series of such compounds - intermetallides which are very brittle. This is common to the entire joint. The thicker the intermetallide layer in the butt the more brittle the joint.

It was established that only during sufficiently thin layers (from 3 micron and less) the joint is not embrittled due to brittle phase at the butt (21).

Therefore, all types of welding with melting are not suitable for welding of steel with aluminum. Of little use for this purpose is the electric resistance welding. However studies in this area are being conducted. The friction welding is the most suitable method of joining aluminum with steel. The metal (aluminum) is not melted and the diffusion processes therefore are not activated. The metal is heated in small volumes and is cooled quickly, which interrupts the beginning diffusion. By large peening pressures (as a result of the plastic deformation of metal) the intermetallides which had time to form in the butt are removed.

However, as studies showed, the heating process cannot be short. Its duration should be sufficient for heating of the face (joining) surface of steel and for deformation, even at micro-volumes, to assure the extraction of dislocations in a number sufficient for the formation of the seizing nodes and to assure the destruction and removal of oxide films from the butt.

For a high quality welding of the aluminum with steel, the face surface of the steel part should be strictly perpendicular to the rotation axis. During deviation of more than 0.2mm the quality of the welded joint is sharply lowered. In addition, the face of the aluminum part should be cleaned from fats and other adsorbing films. For instance, the cleaning can be done with the help of a rotating brush as it is usually done before the cold welding of the aluminum.

As a result of studies (12) welding regimes were found for AD1 aluminum with low carbon steel St.3. These regimes are listed in Table 10. During welding at these regimes the aluminum part is placed into an upset die. The end protruding from the die is indicated in Table 10.

Table 10

Friction Welding Regimes for ADI Aluminum with Steel St.3

Part diameter in mm.	Initial Protrusion from the die.	Rotation Speed in RPM	Unit Pressure in kg/mm2		Heating Time in Sec.	Upset in mm.		Bending Angle in Deg.
			Heating	Peening		Heating	Total	
30	15	1000	5	12	4	10	14	180
30	16	750	5	5	4,5	10	15	180
40	20	750	5	5	5	12	13	180
50	26	400	5	12	7	10	15	100—180

The testing of the welded joints for stress by static loading showed equal strength of the butt metal with the base metal, aluminum. The microscopic studies and the measurements of the micro-hardness revealed the presence of cold hardened aluminum zone with a thickness of up to 0.1 mm adjacent to the butt. In a large enlargement of the microsection the butt has wavy lines.

The studies also revealed the possibility of welding of aluminum with alloyed steels, in particular stainless steels. It was established that during welding of such composition more strict regimes than regimes listed in Table 10 can be used because in this case the diffusion processes in the butt are slowed down.

It is important to emphasize that the joining of aluminum with steel performed under recommended friction welding regimes, which is not brittle, may be embrittled during consequent heating of the welded part. Such heating to temperatures exceeding some critical values activates diffusion processes in the butt area, contributes to the increase in the thickness of the intermetallide interlayer, and as a result, causes the embrittlement of the joint.[1]

Usually, the bimetallic steel-aluminum joints are done on parts which later are welded into a structure with the help of other types of welding. It should be noted that the repeated heating of the steel-aluminum joints should not exceed 400 degrees C in the case of low carbon steel compositions and 550 to 600 degrees in the case of stainless steel compositions.

Recently, studies were conducted in welding of some aluminum alloys with steels. It was established, that low alloyed magnesium and silicon alloys with aluminum base can be welded to steels in a satisfactory manner. As the content of the alloying components in the alloys is increased the difficulties in the direct joining of such alloys with steels mount. For instance, the AMg6 alloys welds very badly with steel. However, the strength and plastic properties of AMg3-steel joints are satisfactory.

To alleviate the friction welding of steel with aluminum under industrial conditions, welding regimes which allow welding without the upset die were developed recently. These regimes were introduced in several plants where steel-aluminum joints of bi-metallic parts with continuous and tubular cross section are mass-produced.

Footnotes to Chapter VII:

[1]Samples, which passed very rigid test conditions, can be fractured by a light blow (brittle fracture).

Chapter VIII

QUALITY CONTROL OF FRICTION WELDING JOINTS

29. The Features of Metal in the Welding Zone

The testing of friction welding joints for elongation, viscosity, torsion, and other always yield good results if the welding was performed under correctly selected regimes. Usually, the temporary resistance of the butt metal to static elongation is higher than that of the base metal during testing.[1] The critical angle, when cracks appear along the butt, is not lower than the angle for the base metal during bending testing. For originally plastic metals and alloys it is usually more than 180 degrees. During torsion testing the fracture in the overwhelming majority of cases occurs not in the butt.

These properties of the joint metal are explained by the fact that there are no macro-flaws in the joint metal. The structure of the butt metal is unique.

If during welding with melting the size of the grain in the butt is significantly higher than in the base metal, then in the friction welding joints the reverse is observed (see Fig. 4). The grain in the butt metal is equiaxial and 10-30 times finer than the base metal grain. No noticeable grain growth is observed in the thermal effect zone during friction welding.

The causes of this phenomenon are not completely clear as yet. Following assumptions are possible:

mechanical refinement (grinding of the grain during friction;

granulation of grains during wearing process of the friction surfaces;

the short time of temperature effect and high cooling rates of small metal volumes heated to critical points.

The possibility of formation of thin metal structures as a result of the combined action of high temperature and very high pressures (4 kg/sq. mm = 400 atm) on the metal cannot be excluded. These conditions of metal processing are not known in the metallurgy. These regimes are close to conditions of thermo-mechanical processing (TMP) which appeared recently. TMP is also based on the simultaneous action of high temperatures and pressures. The properties of the metal after TMP remind one in many aspects of the properties of the friction welding seam metal. The metal is made stronger without loss of its plastic properties.

The absence of macro-flaws in the butt is due to the fact that all foreign bodies covering the friction surface of parts before welding are destroyed as a result of plastic deformation of the metal and are forced out in the radial direction. Only pure metals establish the contact.

The oxide films, which always cover the metallic surfaces are destroyed and removed from the butt zone into the flash together with other foreign additives during friction, heating, and deformation of metal. The feature of the friction welding is that during the entire heating period and later during peening the butt is closed, the friction surfaces are sufficiently close to each other, and their oxidation does not take place during heating. The doubts which arose in the connection with the above were removed by a special experiment. Welding of steel samples was conducted at the same regimes. In one case the welding was done in free air and in the other in pure argon. Oscillograms of the of the friction moments were obtained. In both cases the

curves obtained coincide completely. This can occur only if the surrounding medium is not in contact with the butt because in the opposite case the coefficients and moments of friction would be quite different.

It is known (44) that the friction coefficients for steel on steel friction are several times higher in the air thar in the argon atmosphere.

Thus, the micro- and macro-features of the joint butt metal bring out the favorable features of friction welding when compared with other types of welding.

However, joints which were done with incorrectly chosen regimes may have following defects: nonfusion in the center of the cross section if the heating was insufficient or very short; annular non-fusion along the periphery of the cross section (methods for preventing these defects are shown in Chapter VII).

In addition, joints of raw rods or tubes, which were done by friction welding have reduced dynamic strength. The fracture during testing occurs close to the butt in the thermal effect zone.

This phenomenon is connected with the texture of the stock. Studies showed that the texture fibers, which are usually located parallel to the rod (tube) are twisted during friction welding in the thermal effect zone (macro-deformation zone). The diameter microsections show that this phenomenon is observable as bending of fibers at 90 degrees (Fig. 53). As a result, the fibers of the butt metal are located parallel to the friction surface of the welding part. (Actually, in addition the metal in the butt zone is subject to torsion deformation).

In such parts the places of emergence of fibers at the side surfaces may be sources of rupture and later complete fracture of the joint under dynamic action at the joint if the flash is removed. The annealing of parts can serve as a measure of preventing the fracture of parts. Another method to prevent the reduction of the dynamic strength is the use of strict friction regimes (friction welding with increased pressures or use of increased rotation speeds. Under these regimes, because of short thermal cycle, the thermal effect zone is comparatively narrow (thin) and no twisting of texture fibers is observed. Instead, the fibers break off as they near the butt and remain straight. The twisting of the stock texture has also an effect on the corrosion resistance of the joint. Tests showed that the places of emergence of fibers at the side surface of parts were sources of corrosion, which spreads along the fiber into the depth of the metal. The joints have higher corrosion resistance if the welding is conducted at strict regimes. The corrosion resistance increases rapidly if the flash is not removed from the part.

Fig. 53. The stock texture. Close to the butt the fibers change directions (special etching of aluminum).

Defects in the joints may be due also to careless preparation of parts for welding: slag remaining at the surfaces, cutting of parts with badly adjusted scissors, and others. Defects may occur also because of the misalignment of the welding machine.

Therefore, the quality control of joints (systematic or

periodic, mass or selective) is necessary.

30. The Inspection of the Welded Joint

The introduction of new welding methods is usually difficult because there are no simple and cheap methods of non-destructive inspection of welded joints convenient for use in welding or production plants. Roentgenography, radiography, and magnitography are complicated, expensive and usually are used in production of very important parts. Besides, these methods are convenient for inspection of seams of sheet structures and, practically, are almost unsuitable for inspection of butt joints of massive cross sections.

The ultrasonic defectoscopy is relatively simple and suitable for inspection of butt joints but it has the following deficiencies which force one not to use this method:

the contemporary ultra-defectoscopes do not reveal non-fusion, pores and other defects where area in the plane perpendicular to the ray is less than 0.5% of the area of the cross section being inspected; for a sample with a 20 mm diameter this is 1.5 sq. mm; at the same time it is known that a defect of such a size is not permissible under certain operational conditions of the welded part because it might be a cause for a breakdown;

flash (collar) which was not removed from the part surface is an impediment for ultra-sound defectoscopy and may distort the results of the inspection; if the inspection is done after the flash is removed then the defective part becomes more expensive;

ultra-sound defectoscopes are not suitable for quality inspection of joints in the butt formed by different materials; often, even the difference in the structure of two bimetal joints gives a false signal, which is accepted by the inspector as a

defect when actually there is no defect at all.

Frequently, there are cases where the absence of efficient methods of non-destructive inspection forces one not to use certain welding methods.

The use of selective control with close inspection of the joint quality by any method, including the destructive method, could be basically acceptable for mass production. However, these methods are used comparatively rarely. This is due not so much to organizational difficulties connected with the use of these methods, but to instability in the property of joints of the same batch. There is no confidence that good results received during testing of selected samples can be expected for the entire batch. The reverse case is alsl true: should a large batch of parts be rejected because the test samples were defective.

The friction welding is free from this deficiency to a significant degree.

The friction welding, in contrast to other types of welding, is not affected by outside and often incidental factors. The basic causes in the instability of the quality of joints done, for instance, with the electric welding are the initial condition of the surfaces of the welding parts, oscillations in the electric power supply line, the qualification of the welder and the degree of his fatigue, the air humidity. When the same joint is done with friction welding these factors have almost no influence on the welding process and its result.

The quality of the friction welding joint is determined by basic process parameters. Therefore, the stability in the

properties of the welded joints of parts belonging to the same batch and produced without readjustment of the machine depends only on the stability of the basic process parameters during welding of this batch or, more precisely, on the ability of the machine to maintain the welding process parameters within the required limits.

Considering each of the basic parameters separately it is easily seen that one can obtain any degree of precision in maintaining of these parameters at a pre-determined level by elementary means. Asynchronous three-phase motor, whose rotation speed is practically constant and does not depend on the load or on the oscillations in the power supply line is usually used to drive the friction welding machines.

For pneumatic as well as hydraulic drive of friction welding machine power units the pressure of heating and peening is established with the help of special pressure generators, which are sufficiently precise to maintain an assigned regime and not permit fluctuations of more than plus or minus 5 percent.

The time of heating is usually controlled with the help of electronic time relay of high precision and stability.

Not less precise are special monitoring devices for reading of heating upset, if the heating process is regulated by this parameter.

If necessary the control levers of the machine can be frozen by means of locks. Then the interference of a hum in the welding cycle of the machine becomes completely impossible. The stable operation of the controls will assure the reproducibility of the process parameters from one welding to another. This feature of the friction welding permits the

substantiated use of selective control methods.

To remove all doubts, a special experiment was performed on a large number of samples. The experiment showed that the deviation in the quality of joints welded without readjustment of the machine was not more than plus or minus 7-8% for all indicators for the entire batch.

Such experiments with approximately the same results were conducted at a series of plants, where, after this, the friction welding of even important parts was introduced without doubts and always yielded good results. Based on the above, one can make the following conclusions:

1. the independence of the quality of the welded joints from the effect of a series secondary factors distinguishes the friction welding favorably from all other types of welding;

2. all contemporary friction welding machines assure the maintenance of the predetermined operational regime and the stability of the process parameters, which determine the quality of the welded joint, to a high degree of precision;

3. the combination of these features of the process and the friction welding equipment make it possible to obtain stable quality of the welded joints, and, consequently, to use the methods of selective inspection with confidence that the quality of the entire batch of parts welded without readjustment of the machine will be precisely the same as the quality of samples selected from the batch which were subjected to testing.

The practical use of selected inspection of the quality of friction welding joints at different plants showed that, depending on the degree of importance of the welded parts, on the

organization of production and inspection at the plant and on series of other reasons, the specifications for selection of samples are different.

The testing method of the selected samples is of interest. It was indicated above that the metal in the butt has better temporary resistance than the base metal for correctly selected friction welding regimes. Thus, the testing of samples for tension cannot guarrantee the absence of fine defects in the butt. It is not advisable to apply these tests to parts which are intended for operation under dynamic loads.

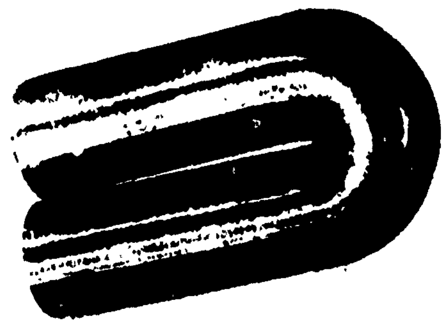


Fig. 54. Copper sample, 40 mm diameter, after friction welding, flash removal, and bend testing (without thermal processing).

The testing of samples for bending was used in our laboratory extensively for preliminary selection of the regime. The macrodefects and other flaws in the butt metal and the adjacent thermal effect zone were revealed sufficiently, as experience shows. During bending, the external fibers of the part under test are subjected to large yield points in the base metal. At the same time, the plasticity of the joint is controlled well during bending because the same external fibers undergo significant deformation.

Many enterprises which use friction welding and the selected inspection of the joints include the bending in their obligatory program for testing of parts.

The Scientific Research Institute of Welding Equipment

uses a more strict regime than the State Standard in bending tests of samples if the plasticity of the material permits it. The sample is bent at 180 degrees (Fig. 54) to flattening. During testing of tubular parts the joint is usually cut along the formed tube into strips with a thickness of 5-10 mm (depending on the diameter and the thickness of the sample walls) after removal of the flash. Then each such strip is subjected to bending test. For simplicity, the cutting is done not along the entire length of the tube but in such a way that the butt is cut. Each strip is then bent to an angle (Fig. 55) at which first cracks appear. This method is also often used by the plants.

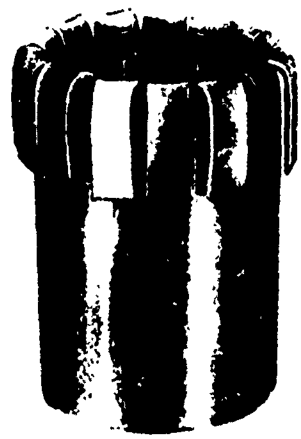


Fig. 55. Steel-aluminum bending sample with tubular cross section.

At the present time, B.I. Merninov at the Scientific Research Institute of Welding Equipment is developing a procedure for determining the properties of the butt metal by tension testing (41). The sample is given a special profile with the help of a lathe. Its body is made thinner in the butt region with smooth transitions to the original diameter. This procedure yielded good results according to the preliminary data.

However, for better reliability it is expedient to subject the selectively chosen parts to such loads. which correspond in their loading scheme to the normal operational conditions of the part and in their magnitude will insure the required reserve of strength and plasticity.

Footnotes to Chapter VIII:

[1]To determine in these cases the temporary resistance a neck (with a smooth transition to the base metal) is cut at the butt.

Chapter IX

FRICTION WELDING EQUIPMENT

31. The Use of Metal Cutting Machines

Friction welding originated on the lathe. A.I. Chudikov manually welded low carbon steel rods of 30 mm diameter on a DIP-200 machine without any modifications, and a DIP-300 was found suitable for welding 50 mm rods diamter steel rods. Here, one specimen is fastened to the support (for instance in the cutting tool holder) or into the tailstock and the other is gripped in the chuck of the spindle of the headstock. Such use of operating lathes may seem in many respects very desirable at first; however, after further investigation it proved to be objectionable.

The operating conditions required for friction welding (high axial forces at comparatively high rotation speeds) for whcih, as rule, metal working machines are not designed, soon disables them. The considerable radial vibration encountered in the initial stage of welding process also contributes to this.

Moreover, many machines cannot operate under the conditions of rotation speed and axial force required for friction welding.

Finally, metal working machines, with rotating parts having large flywheel masses and which are not equipped with special barking or clutches (for disengaging the spindle of the head stock from the remaining elements of the driving gear while in motion) cannot be stopped instantaneously and, consequently, the quality of the welding connection is impaired.

Sometimes, the weld cannot be made at all on such machines.

The use of metal working machines is not permissible for friction welding.

Thus, there remain two possibilities for friction welding equipment: 1. reconditioning and modification of outmoded and unused metal working machines, particularly lathes; 2. development of special machines.

These alternatives have been discussed for some time. As the friction welding became accepted in the industry it became apparent that special equipment was necessary for this process.

Actually, remodeling of outdated lathes and other machines, a course of action taken by some concerns, is not expedient for the following reasons:

1. When remodeling old machines one utilizes, as a rule, only very few assemblies (bed, tailstock). At the same time, the other assemblies are either replaced with newly manufactured ones or are subjected to complete rebuilding. It is known that under certain conditions, even a thorough overhaul is more expensive than acquisition of a new machine. The reconstruction of lathe into a friction welding machine is a task considerably more complicated. It always involves large expenditures for labor and materials and costs no less than a new special machine for friction welding.

2. Such overhauling of metal working machines would be undertaken on an individual basis without outside help, for example, in factory workshops. It is quite understandable that centralized production of special friction welding equipment is

first of all considerably more profitable, and secondly it will provide the industry with equipment of much higher technical standards that will more closely conform to the requirements for specific operational conditions than the adopted and overhauled existing metal working equipment.

Suggestions were made to organize a "small-scale modernization program" which would involve low expenditures that could be afforded by any metal working plant (37). The adoption of such a program would have led to a manual performance of nearly all operations on such machines (the application of the axial load and stopping of the rotation would be performed manually without regulation of the load and the process would have been entirely controlled by time).

This would preclude the utilization of one of the basic advantages of the process - uniform quality of the weld, since in this case its mechanical properties would have been entirely determined by skill and experience of the welder.

The required operating conditions, particularly insofar as the axial load is concerned, cannot always be met on such equipment. This leads to a more drawn out process as a result of inadequate heating intensity and the coarse grained structure of the metal in the joint. In addition to the fact that there is insufficient force to produce the upset, a metal structure of this type gives a welded connection of low strength. Small scale modernization can be utilized, however, in those exceptional cases where friction welding will be applied only to details of secondary importance.

The Scientific Research Institute of Welding Equipment and later other organizations as well (Minsk Tractor Plant, TsNIITmash,

NIItraktorosel'khozmah, Chelyabinsk NIPTIAMmash, and others) adopted the more promising alternative of developing special equipment for friction welding. The same path was chosen by foreign firms in USA, Great Britain, Japan, Poland, Federal German Republic, France and in other countries.

32. Basic Requirement for Friction Welding Equipment

The experience gained from research on friction welding, the development and introduction of the metal welding technology, the study of the requirements of the industry and the results of operation of several hundred machines form the basis for the formulation of the fundamental special requirements of such equipment. These requirements can be divided into two groups - general and special. The general requirements are high productivity of the equipment, high degree of mechanization of the process (in a series of cases), complete automation, maximum universality, simplicity of maintenance, small power consumption, small weight, small size, maximum unification of parts and subassemblies of machines, simplicity of repair and others.

The sepcial requirements can be divided into two groups: technological and design.

Among the number of the technological requirements are the coordination of the technical characteristics of the machines with the required friction welding process parameters for given combination of metals (alloys). The machine should provide for:

1. the required pressure cycle,
2. strict and repeatable heating process regulation by time or by length of upset,
3. swift (instantaneous) stopping of the relative rotation at the end of the heating period,

4. semi-automatic welding cycle which makes it possible to obtain joints with the same quality without readjustment of the machine.

The design requirements are as follows: they should assure

1. the relative rotation of one of the welding parts relative to the other with simultaneous application of the axial force - heating force,

2. adequate rigidity of the load carrying components of the machine to eliminate radial displacement of the welded specimens during operation of the machine, and damping of radial vibrations created by the welding process,

3. reliable gripping of the welded specimen in the machine which will withstand the maximum friction moment and the axial force,

4. an adjustment regime in the operation of machine during its adjustment or change-over.

The general purpose machines have following additional requirements:

1. the possibility of welding of short as well as long specimens,

2. welding of rod as well as tubular specimens,

3. the possibility of welding T-joints (welding a rod or tube to a flat surface part,

4. the possibility of use of various clamps according to the shapes of the welded specimens and the ease of interchanging one type of clamps for another.

Let us consider some of the indicated special requirements.

Rapid stopping of the relative rotation

Rapid stopping is of importance during welding of relatively small diameter parts. When welding large diameter parts slower machines are usually used and, consequently, the rotating parts of these machines have a lower kinetic energy. At the same time, the resistance moment of the specimen increases with increase in the diameter and the braking effect due to friction moment in the butt is increased. In this case the swiftness in the braking at the end of the heating is an important condition for obtaining good quality joints.

Four principal techniques of rapid stopping of the relative rotation of the specimens are used:

1. artificial braking of the entire driving mechanism including the rotating specimen for example by electromagnetic braking, reversing of the motor, etc.;
2. disconnection of the chuck holding the rotating specimen from other parts of the drive (for instance by an electromagnetic coupling) and braking with the moment of the friction surfaces of the specimens or using a separate brake;
3. the release of the originally stationary specimen at the end of the heating cycle (the moment acting on it induces rotation) and the relative speed of the specimens becomes zero; cooling and creation of the final connection takes place with both specimens rotating;
4. release of the stationary specimen at the end of the welding cycle followed by forced rotation as a result of engagement with a separate drive or the same drive (for both specimens).

Machines which utilize one of the first two techniques are more flexible in their operation, since one of the specimens can

be of practically unlimited length, diameter, and mass. The rotating part should have small mass for its instant stoppage at the end of heating. Pieces, whose both parts have relatively small diameters, length, and mass should be welded using the third and the fourth methods for stoppage of the relative motion.

Of all the techniques mentioned above, braking of the motor should be given preference from the standpoint of design and operational reliability. However, it should be noted that this complicates the operating conditions of the motor (overhauling because of frequent starts and stoppages) and the efficiency of braking is lowered with increase in the motor temperature.

Many Soviet and foreign machines utilize the second method of braking with the help of reversing couple. This requires some complication in the design of machine. However, very effective braking results.

Our comparative studies (using oscillography) of the "coasting" of the shaft for two machines with identical power (20 kw), with identical rotation speeds (1000 RPM) and identical inertial moments of the rotating parts of the drive showed that in the first case the braking path consisted of 2.5 to 3 revolutions. However, during braking using the frictional coupling with simultaneous disengagement of the shaft from the drive the braking path was not more than 0.5 revolution.

Some artificial techniques can be used to increase the braking effect: a. the use of a stepped pressure cycle to increase the braking moment due to friction in the butt; b. the use of a machine with two shafts rotating in opposite directions at half of the relative rotation speed each.

It should be mentioned that the last technique (b) and braking methods 3 and 4 were not used so far apparently because of the complexity in design.

Requirements for Gripping devices

To reduce costs and to simplify the machine, manual gripping of the part should be used on machines producing custom products or small quantities. In all other cases, loading of the machine should be accomplished by fast acting devices not requiring physical exertion of the operator.

All gripping devices must be extremely reliable in holding the specimen. The slightest dislocation of the detail to be welded in the chuck during the welding process leads to welding of the specimen to the gripping device or wear or damage of the device. The welding requirements for specimens of unlimited length very often make it impossible to utilize the supports for transmitting the axial reactions from the gripping devices. Such "supportless" gripping devices must resist considerable axial force to allow the part to rotate. The gripping devices should be designed for maximum friction moment which can be 2 to 2.5 times larger than the moment computed on the basis of installed power. As experience has shown, the design of the friction welding machines should be based on a gripping force of 2.5 to 4 times the maximum axial load developed by the operating cylinder of the machine.

Automation of the friction cycle

Depending on the intent and the proposed conditions the friction welding machine operations may be either with manual control of the secondary operations using semi-automats where the

installation and removal of the parts is done manually and the rest of the cycle is automatic or with automats, i.e. machines which can operate for extended lengths of time without human interference.

However, no matter what degree of automation is used, the friction welding machines are inherently automatic during the welding cycle. Thus, they assure stability in the required process parameters. Otherwise, one of the most important advantages of the friction welding, the uniformity in the quality of the welded connections, is not obtained.

33. Suggested Types of Friction Welding Machines and Proposed Scales

Industrial equipment for friction welding can be divided into two basic groups: general purpose equipment (in this sense universal) and special purpose equipment.

Machines of the second group are intended for welding of one part or groups of parts of the same type, whose dimensions or materials are known when the machine is designed. In most cases these machines must be automatic or semi-automatic and are designed for operation under mass production conditions. Such machines are usually produced in single numbers.

Their parameters cannot be determined in advance, since this would restrict the designer and lead to creation of clumsy and inefficient design. Therefore, it is desirable to design sub-assemblies of these machines first from which special purpose machines could be designed later on.

A completely different approach is necessary for general

purpose machines. The mass produced machines must have very definite and efficient characteristics corresponding to the various conditions of their operation. However, the experience gained in the design of such machinery and in experimental research on friction welding has shown that in practice such machines can be designed for only a limited flexibility of operation. For example, though it is desirable to use the same machine for welding specimens with a minimum diameter of 8 to 10 mm and a maximum diameter of 50 to 60 mm, this cannot be accomplished in practice. It should be pointed out that such a machine would have to permit adjustment of the shaft speed from 2000-2500 to 400-500 RPM, of the axial load from 300 to 30,000 kg, and would require a power consumption of 3-60 kw.

A machine designed to the above specifications would require very rigid and heavy load carrying components and a powerful motor for large diameter specimens. The machine would also have to be supplied with a power reducer and transmission and other components. All this would lead to tremendous difficulties when stopping rotation in the manner required for welding specimens of small cross sections rotating in this case at large speeds (2500 RPM).

Experience has also shown that friction welding of specimens of small cross section on powerful machines involves numerous technical difficulties and is more complicated and less profitable than welding on machines specifically designed for this purpose.

For welding of parts with 10 to 66-70 mm diameters a series of machines should be designed each of which having a different diameter range. Taking this into consideration, the Scientific Research Institute of Friction Welding developed two approximate

scales for tentative break down of the types and sizes of the friction welding machines and their basic characteristics. This break-down applies to friction welding of parts from low carbon steel with a diameter from 10 mm to 60-70 mm. The following requirements were taken into consideration:

1. the number of different types of machines should be kept at a minimum;

2. each machine should operate at only one rotation speed to keep the design of the machine simple;

3. the ratio of the minimum axial pressure to the maximum should not exceed 1:10 (for pneumatic equipment this ratio is preferably no higher than 1:5) to satisfy the control characteristics of existing pneumatic and hydraulic equipment;

4. the design of the machine should be very simple;

5. the weight of the machine should be kept to a minimum.

An attempt to incorporate these conflicting specifications from the point of view of the operation of the equipment as well as its manufacturing led to the development of two scales for types and sizes of general purpose friction welding machines.

<u>Scale I</u>

Type and size of machine.....	I	II	III	IV
Diameter of the welding parts in mm..	to 10	8-25	20-40	35-60
Axial load in kg.............	to 1000	5000	10 000	30 000
Rotation speed in RPM........	2000	1500	1000	600
Power requirement for welding in kw..	to 3	10	20	60

<u>Scale II</u>

Type and size of machir	II	III	IV	V
Diameter of the welding parts in mm..	10-25	16-36	20-50	32-70
Axial load in kg.............	5000	10 000	20 000	40 000
Rotation speed in RPM........	1500	1000	750	500
Power requirement for welding in kw..	10	20	40	80

The second scale satisfies better the requirements of the industry and was used by the Scientific Research Institute of Friction Welding for design of general purpose machines, which are now mass produced at the Volkovysk Plant of Casting Equipment.

34. Features in the Design of Contemporary Friction Welding Machines

The contemporary friction welding machines are sufficiently complicated, varied, and consist of a large number of elements and sub-assemblies. They will not be considered here in detail. Below we list only some of the features of their design.

Basic sub-assemblies of the machine

The friction welding machines usually consist of following subassemblies (Fig. 56): two clamps 5 and 7; the parts to be welded 6, one of which is rotated; headstock 4 with a shaft which

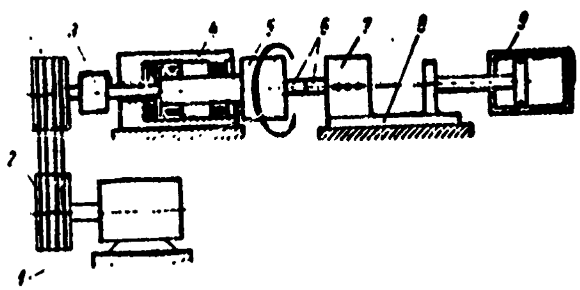


Fig. 56. Principal structural-kinematic diagram of contemporary friction welding machine.

includes the rotating clamp 5; sub-assembly 8 where the non-rotating clamp is located; drive mechanism of the shaft with motor 1, belt drive 2 and a device for belt adjustment[1]; frictional coupling 3 for coupling of the shaft with drive and for braking of the shaft, pneumatic or hydraulic cylinders 9 which insure the

necessary operational (axial) force of the machine; pneumatic, pneumatic-hydraulic or hydraulic circuit for the control of the power drive of the machine; electrical circuit for the control of the machine; machine base; control panel.

Two basic structural-kinematic schemes for general purpose machines

Depending on the use of the machine the design can be performed according to the two following structural-kinematic schemes:

1. only one part is rotated and displaced axially the other remains fixed in space;
2. one part is rotated and the other is displaced axially.

The first of these schemes should be used in cases when one of the welding parts is long, massive and there is danger that its inertia during the upset process (during heating and especially during peening) will inhibit the application of the necessary axial force. This scheme is the basis of four types of machines developed by the Scientific Research Institute of Welding Equipment (VNIIESO) and which are produced at present time by the Volkovysk Plant of Casting Equipment.

The second scheme is suitable for welding of relatively short parts. In this case, the clamps may have supports which absorb the reaction of the axial force. But in the design of such a machine one has to consider, besides the axial displacement of the clamps during upset, the possibility of moving the clamps after welding along a distance which is not less than the length of the welding part for adjustment. The first friction welding machine in the world, MST-1, was designed according to this scheme. The machine was developed VNIIESO. The Moscow

Plant "Frezer" uses the basis of this design at present time in manufacturing of the special semi-automat MF-327 for friction welding of cutting tool parts. According to the scheme VNIIESO built special automats MSTA-31 and MSTA-32 for welding of drills and bores.

Machines built according to the first scheme have a more complicated headstock structure because the shaft does not only rotate but has to be displaced along the axis together with its bearings. The bearings are placed into a container, which can be displaced inside the structure of the headstock with the aid of a pneumatic or hydraulic cylinder which is mounted in the head structure. The remaining sub-assemblies of the machine are comparatively simple because the second clamp is stationary and fixed rigidly to the frame of the machine. Machines designed in such a manner should have a rigid and strong upper frame flange because it has to resist the bending moment acting in the longitudinal vertical plane of the machine (caused by the axial force) and the torsion moment (reaction friction moment).

The headstock for machines built according to the second scheme is of simple design (for instance MST-31-2 machine). It consists of a shaft with a clamp, bearings, and the headstock body. However, the rest of the design of such machines is more complicated. The axial displacement of the clamp with the non-rotating part can be accomplished by using guides in the form of dovetails (MST-1, MF-327, MST-31-2) or using 2 or 3 annular guides (MSTA-31, MSTA-32, MST-1001, and others). The second version is preferred because in this case the axes of both guides and the axis of the machine may be located on the same plane. This excludes the transmission of the bending moment to the frame of the machine. The frame in this case should be sufficiently rigid because 1. its upper frame absorbs the torsion moment and

2 the lower or the side location of the motor, the tension of the belts and vibration of the upper part of the machine during operation requires rigidity in the remaining parts of the frame

The power drive system

The power drive system of the machine has to insure a uniform value of the axial force and its change according to predetermined program "heating-peening". This completely eliminates the possibility of a motor drive which can insure the predetermined dislocation speed but cannot provide uniform force[2]

The friction welding machines use one of the following types of power drive: pneumatic, pneumatic-hydraulic, or hydraulic

The pneumatic drive is usually supplied with low pressure (4-5 kg/sq. cm) air and with an operating cylinder and is used in low power machines intended for welding of small cross section parts. With increase in the active force of the machine one has to use pneumatic-hydraulic or completely hydraulic power drives to avoid large operating cylinders (for a 5 ton force machine a cylinder of about 400 mm piston diameter is needed).

The hydraulic schemes are complicated, capricious during operation, and bulky. They can be recommended only for high power machines whose axial force is more than 100 tons All intermediate machines (5-100 tons) should use pneumatic-hydraulic power drives. These machines have small operating cylinders because they use high pressure oil from special pneumatic hydraulic pressure converters installed on the frame of the machine and connected with the operating cylinders by rigid or elastic oil lines. Despite the fact that the compressed air energy is most expensive when compared with other types of energy, the

convenience of the pneumatic-hydraulic drive systems specified their use in most designs of Soviet friction welding machines.

Such machines should use a reservoir to insure uniform pressure of peening. The volume of these reservoirs should be 8-10 times the consumption of air for one pass of the machine). If the air in the compression line is not clean, filters and moisture separators should be installed before the machine.

Bearing sub-assemblies of the machines

The rotation of one of the parts common in friction welding is brought about by a shaft imbedded in two crank bearings. The axial (operation) force of the machine is absorbed by a support bearing. Calculations have shown that in majority of cases it is expedient to substitute one of the radial bearings by a radial-support bearing with support bearing function.

The combination of the rotation speed with significant operational forces common in friction welding is not favorable for operation of bearings. Therefore, sliding bearings cannot be used. Usually one uses either roll or ball bearings.

The existing assortment of these products very often puts the designer in a difficult position. One has to use double, and sometimes triple, support or radial-support antifriction bearings.

The bearing problem is one of the causes which limit the application of high power machines. Extensive research and design work has still to be done in this field.

The conversion to increased rotation speeds during friction

welding is not desirable from the point of view of [illegible] and reliability of the bearing this will even more complicate the operation of bearing sub assemblies and sharply [illegible] the efficiency coefficient

The operational conditions for the bearings are complicated by the character of the radial loads at the shaft. Experiments have shown that during the heating in friction welding, especially in its first phase, significant alternating dynamic forces arise in the butt plane (in radial direction). The appearance and the magnitude of these loads are not connected with the nonparallelism of the friction surfaces during the first instance of their contact (this creates additional impact loads). The dynamic radial forces are characteristic of the initial stages of the setting process because the sources of setting are not located on the rotation axis.

This phenomenon should be considered during design of bearings and also during arrangement for their location because radial forces reach significant values. For instance, during welding of low carbon steel parts with a 25 mm diameter, radial forces of 400-450 kg were recorded with the help of tensometric sensors and oscillograph.

The location of the bearings at the shaft so that the front (relative to the place of the welding) bearing absorbs only radial loads and the rear bearing is a radial support bearing is considered expedient at present time. The axial force is transmitted along the entire shaft which is thus subject to buckling. The dynamic coefficient should be assumed low during design of the front bearing.

Gripping devices

To grip the piece during welding, when considerable moment and axial force are applied at the same time, it is necessary that the sum of the normal forces transmitted from the sides of the clamp to the part should not be more than four times the axial operation force developed by the machine.

If the welding is conducted using clamps with supports and the axial force is absorbed by them then the total radial force of the clamps can be reduced to 1.5 to 2 times the axial force.

Such large forces cannot be provided by the usual chucks of hydraulic drive lathes. The standard three jaw chucks with manual drive make it possible to obtain the needed force at the expense of a longer lever and the application of significant force. The frequent change of parts (two and more times per minute) tires the worker, reduces his productivity, and chucks wear out quickly under these conditions.

The friction welding machines should be supplied with mechanized grips which were specially designed for this purpose. Such grips should be self centering. In addition, it is desirable that the rotating grip should have a minimum moment of inertia. It is desirable that the control of such a mechanized grip should be automatic, including it into the general operation cycle of the machine.

Electrical equipment

The electrical control circuit is based on the [illegible] [illegible] most [illegible] machines. Attempts to place the electrical components inside the frame of the machine were not

successful. Vibration of the machine, impacts during the switch-over of the coupling during application of the peening force and in other cases caused wear of the equipment which damaged the operation of the machine.

In all recent VNIIESO machines all relays, signal lamps, and other impact sensitive parts of the electrical circuit are located on a separate control panel. The control panel includes also all auxiliary control devices. Only control elements for the welding operation cycle of the machine remain in the machine.

35. General Purpose Industrial Equipment

VNIIESO developed four types of semi-automatic machines: MST-23, MST-35, MST-41, MST-51.

The general appearance of one of these machines is presented in Fig. 57.

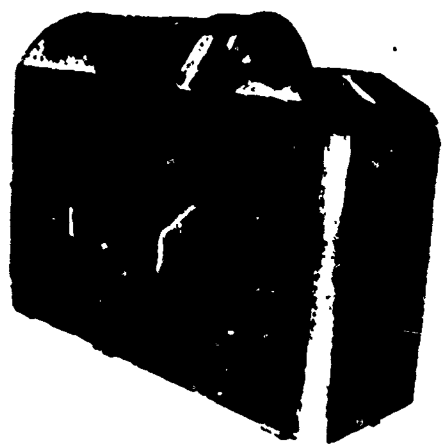


Fig. 57. Semi-automat MST-35.

All four machines are similar in design and geometry. They differ only in the size of cross sections which can be welded on each and, consequently, in the magnitude of the basic parameters.

The technical characteristics of the machines of this series is given in Table 11.

They are intended for welding of rod (continuous cross section) annular pieces from low carbon or low alloyed steels.

These machines permit also the welding of tubular pieces and T-joints.

Besides the indicated materials, the machines can also weld parts from other ferrous and non-ferrous metals and alloys.

The machines can weld under stepped and constant pressure cycles (Fig. 29). With the help of an electrical switch the machines can be easily transferred from the control of heating by upset to control of heating by time and vice versa.

The machines consist of the welding machine itself and the electrical control panel (the later as well as the electro-pneumatic circuit are standardized for all four machines).

The machines of each type have only one rotation speed of the shaft. This, however, does not prevent welding of a sufficiently wide range of cross sections.

The ratio of the minimum cross section to the maximum cross section in each machine is 1:5.

The rotation of the shaft is accomplished with an asynchronous electrical motor using a v-belt transmission.

The power drive system is pneumo-hydraulic. The machines are supplied from a plant line with low pressure compressed air and have pressure converters, which convert this pressure into high pressure in the hydraulic system of the machine. From here, the operating cylinder which develops the necessary force for welding is supplied by high pressure. The force during heating and peening is controlled separately and smoothly with the help of two pressure regulators having manual drives.

Table 11

Characteristic	Unit	Machine type			
		MGT-23	MGT-36	MGT-41	MGT-51
power (nominal)		10	22	40	75
axial force:					
heating to	kg	2500	5 000	10 000	20 000
maximum	kg	5000	10 000	20 000	40 000
diameter of welding rod pieces:					
minimum	мм	10	16	22	32
maximum	»	25	36	50	70
diameter of tubular pieces: maximum	»	32	39	52	75
diameter of disk pieces: maximum	»	110	180	180	320
length of the rotating piece:					
minimum	»	45	50	60	65
maximum	»	600	500	900	1200
length of the stationary piece:					
minimum	»	50	60	70	80
maximum	»	no limit			
heating time	sec	10—20	10—30	15—45	20—50
peening time	»	1,5—2,0	1,5—2,0	1,5—2,0	1,5—2,0
productivity	weld-ings/h	to 150	to 120	to 100	to 70
power supply voltage	V	380	380	380	380
air pressure (nominal)	kg/$см^2$	4,5	4,5	4,5	4,5
machine dimensions					
length	мм	1825	1800	2150	2910
width	»	580	720	770	1110
height	»	1250	1300	1350	1675
central panel dimensions:					
length	мм	470	470	470	470
width	»	400	400	400	400
height	»	1000	1000	1000	1000
weight of machine	kg	2000	2700	3600	5500
weight of control panel	»	85	85	85	85

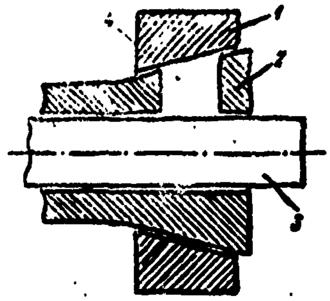
From the working cylinder, the force is applied through the shaft to the rotating part, which can be displaced along the axis. The other welding part is fixed stationary. The machines are supplied with reversible friction couplings which make it possible to rotate the shaft or to instantly braking it (the braking path of the system rotating at 1000 RPM is not more than 0.5 turn).

The machines have push-button controls. All operational and adjustment elements are in the front. Auxiliary starting and control equipment is located in the control panel. The entire welding cycle is automatic after engaging the corresponding control at the control panel. The only manual operations are the installation and the removal of pieces.

The clamps are self-centering. The allowable misalignment of the axes of the pieces (before and after welding) is not more than 0.5 mm. In both clamps, the rotating and the stationary, the pieces are installed using relatively small force. The final installation of the pieces in the clamps is done under force which is proportional to the operational (axial) force of the machine.

The rotating clamp is a tri-jaw interchangeable chuck (Fig. 58). The jaws are interchangeable. Each set of jaws is designed for gripping of pieces within a narrow diameter range (2-3 mm). The machine has 4 sets of such jaws. A greater number of jaw sets is optional and can be ordered from the manufacturer after specifying their size.

The stationary clamp has a pair (in some machines 2 pairs) of interchangeable jaws (Fig. 59) which are suitable for the entire range of diameters for a given machine.



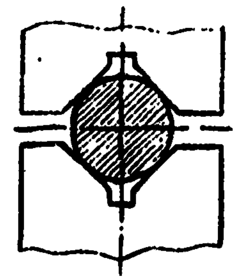


Fig. 58. The design scheme of the rotating chuck. 1 - ring; 2 - clamp body; 3 - welding part; 4 - jaw.

Fig. 59. Profile of stationary clamp jaws.

The basic version of any of these four types of machines is intended for welding of rod pieces with continuous cross section.

The tri-jaw clamps make it possible to clamp thick-wall tubes without danger of crumpling and distortion in the profile of the cross section.

The design of these machines provides for modification of the clamps according to the character of the welding parts.

1. For welding of thin-wall tubes and tubular pieces the clamps with narrow jaws should be replaced with clamps with wide jaws, which grip the piece along its entire periphery. The working surface of such jaw should be tooled to the size (diameter) of the welding part.

Such a clamp will allow to grip a thin-wall tube without crumpling and, when necessary, will straighten out the tube. The gap between the side surfaces of the jaws after installation of the tube should not be more than 1-1.5 mm.

2. For welding of T-shape joints the rotating tri-jaw chuck intended for gripping of rods may be replaced by a chuck of the same design which allows the gripping of disk pieces.

3. For welding of T-joints where the flat part is not annular, a special face plate with a notch can be placed at the shaft clamp (this will eliminate the automatic opening of the clamp). This face plate is of the same shape as the welding part. The welding part is placed at the face plate before each welding. The piece cannot fall out during welding because the other part pushes it against the face plate. Furthermore, the piece cannot turn in its bed. Thus, there is no necessity to clamp it.

4. An analogous method is used to clamp the flat part if it has openings located at the periphery. In this case the face plate is provided with pins which fit into the openings.

In the cases listed above, the annular piece is installed into the stationary clamp. However, it is sometimes necessary to weld a short or tubular part to a massive, bulky piece. In these cases the cylindrical part is installed in the shaft clamp of the machine and the massive piece in the stationary clamp. If the size of the clamp does not permit the installation of the massive part, then a typical stationary clamp can be replaced by another specially designed and more suitable clamp.

During welding of parts from different metals when the use of the upset die is required, the typical stationary clamp allows the installation of a special device carrying the die, thus, fixing the position of the die relative to the welding parts without disturbing their centering.

Modified general purpose machines are used for other special

purposes. MST-35-4 machine for welding of forged yoke with an annular rod (as in Fig. 88) is operating at the Likhachev Plant.

The problem was solved by clamping the forging with special jaws of a typical stationary clamp.

The modified machine MST-23-6 where one of the clamps was changed to conform to the shape of the welding piece is used for welding of stamped brass pieces with annular brass rod.

The parameters of machines MST-23, MST-35, MST-41, and MST-51 were calculated for conditions common in friction welding of low carbon and low alloyed steels: peening unit pressure 10 kg/sq. mm, the unit power consummed 20 w/sq. mm.

The values for the ranges of the welding piece cross sections (diameters) listed in Table 11 were obtained based on the axial force and the consideration of the technically necessary unit process parameters.

In cases where different values of process parameters are necessary (for instance, the peening pressure during welding of tools should be not less than 13-15 kg/sq. mm) for good quality joints the general purpose machines can be used. However, the value of the maximum cross section will be smaller. In the example cited, the maximum cross section of the pieces will be 1.5 times less and the diameter $\sqrt{1.5}$ times less than values given in Table 11.

It is apparent from this short description of general purpose machines and their technical characteristics that basically they are intended for use in mass production of different parts with different purpose, shapes and materials.

The Volkovysk Plant of Casting Equipment mass produces almost the entire gamut of these machines.

The experience gained in the operation of these machines has shown that under normal operational load of the equipment significant economic efficiency can be achieved (in particular, see Chapter X).

36. Special Purpose Industrial Equipment

Besides general purpose machines, numerous special purpose machines have been developed, manufactured, and successfully operated in the Soviet Union for more efficient use of friction welding of only one part (or a group of the same type parts) under mass production conditions.

Among them are:

machines of SMST series developed and adopted for mass production of some tractor parts at the Minsk Tractor Plant;

semi-automat MF-327 for welding of tool cutting parts; the semi-automat was developed by the "Frezer" plant and the design was based on the first friction welding machine MST-1;

equipment developed by VNIIESO including the automats MSTA-31 and MSTA-32 for welding of cutting and measuring tools, semi-automat MST-10.01 for simultaneous welding of two butts (with rotation of a third body and stationary mutually oriented outer pieces), the MST-100.01 machine for welding of tubes (most powerful machine in the Soviet Union);

semi-automat MST-31-2 with cutting support for machining of the face of one of the pieces before welding (developed by VNIIESO) intended for friction welding of short pieces made from different metals for custom and small volume production;

semi-automat MST-6 (developed by VNIIESO) for welding of

T-joints of a copper pin with a diameter of 10 or 12 mm with a copper plate 2 mm thick. The machine can weld at a rate of 420 pieces per hour and successfully replaces the manual soldering (61);

semi-automat (18) for welding of the steering wheel of an automobile (developed by Chelyabinsk NIPTIAMmash).

A number of other special purpose machines for friction welding of different parts were designed by numerous Soviet organizations for their own need and the need of others. More than 40 types of friction welding machines were developed, built, and successfully operated in the Soviet Union. The overwhelming majority are special purpose semi-automats. Table 12 and Fig. 60-65 present characteristics of some of them.

Table 12

Technical Characteristics of Special Friction Welding Machines

Machine	Power in kw	Rotation Speed in RPM	Maximum Force in Tons	Welding Part Diameter in mm	Productivity in Welding/hr.
SMST-3	10	1400	4,5	26	70
SMST-4	20	680	10	38	70
SMST-7	14	1100	8	30	100
MF-327	10	1500	5	10-18*	160
MST-6	4,0	2000	0,8	12	420**
MST-31-2	28	1000	14,0	up to 50	50-60
MSTA-31	22	1000	10,0	14-30*	100-120
MSTA-32	22	1000	10,0	14-30*	100
MST-10.01	40	1000	10,0	33	140***
MST-100.01	125	800	80,0	140/80	6-8
For welding of the steering wheel	4,5	3000-5000	0,1-0,5	10	-

* Special steels are welded
** Copper is welded
*** Simultaneous welding of two butts

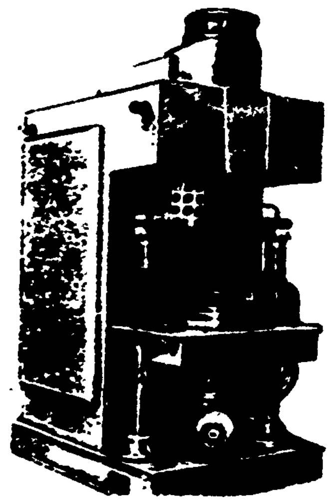


Fig. 60. SMST-7 Machine for welding of crown wheel with shaft (Fig. 87) for take off of MTZ-50 tractor.

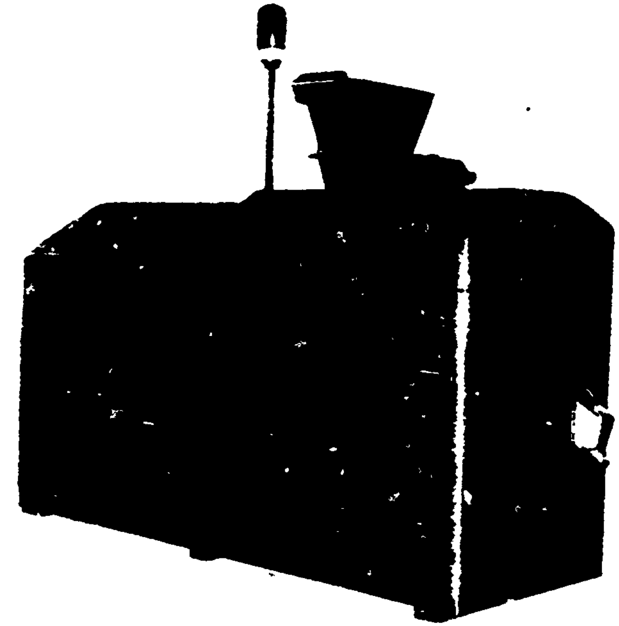


Fig. 61. Automat MSTA-31 for welding of parts of the cutting tool (R18 + structural steel).

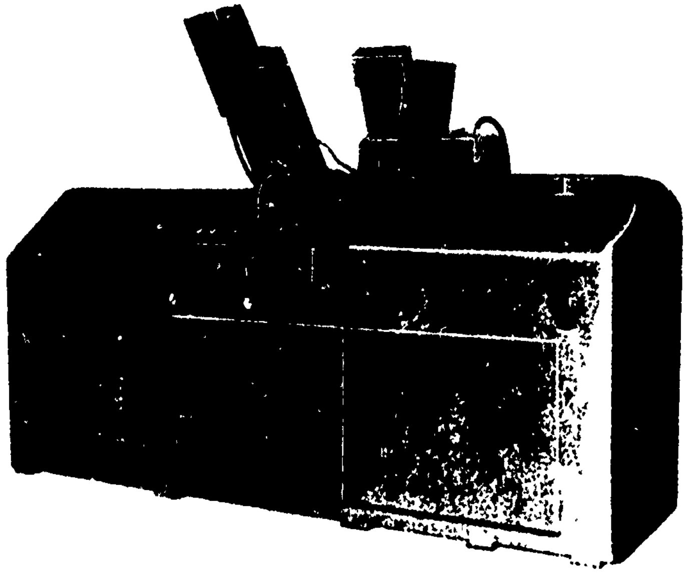


Fig. 62. Automat MSTA-32 for welding of caliper parts (SHKH steel + structural steel.

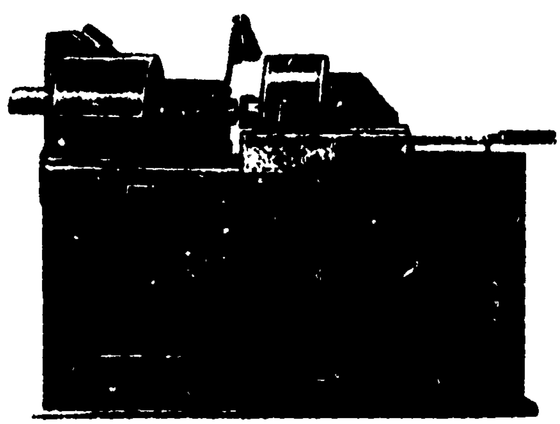


Fig. 63. Semi-automat MF-327 for welding of cutting tool parts (R18 steel + structural steel).

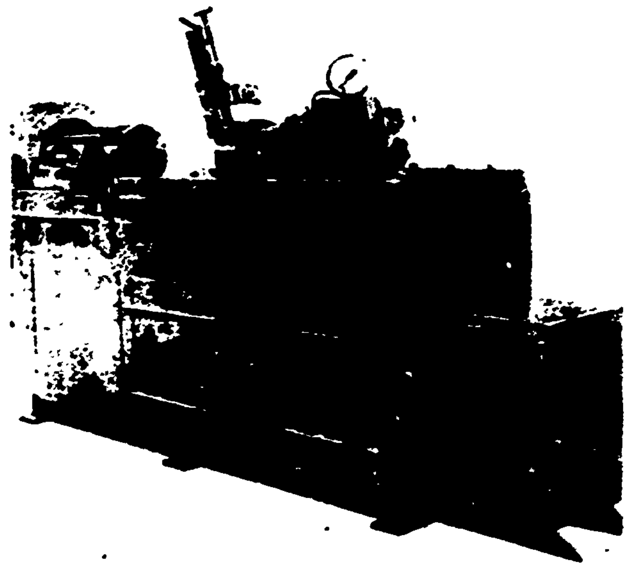


Fig. 64. Machine MST-31-2 with hinged cutting support.

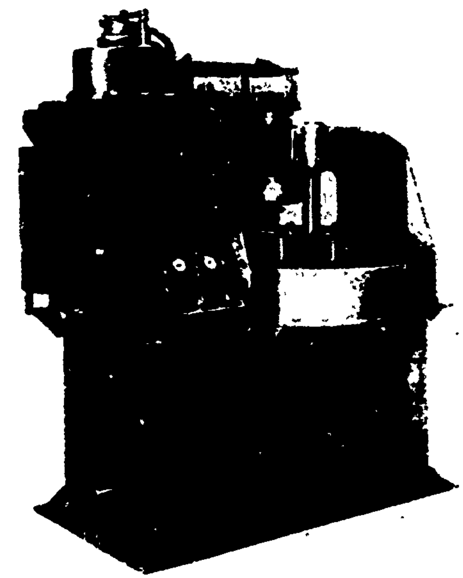


Fig. 65. Semi-automat MST-6.

37. Foreign Equipment

The popularity of friction welding grows steadily abroad. Following the Soviet Union a series of other countries have been conducting studies in this field for comparatively long time. Thus, the American firm AMF began developing the technology and equipment for friction welding in 1959 (64). Somewhat later, several firms in Japan took up friction welding research. At present time, several firms in Great Britain work in this field.

In the British and the Japanese Welders Associations there are special friction welding sections. Friction welding studies are also pursued in Czechoslovakia, Poland, and German Democratic Republic. The West German firm KUKA recently published the results of its work. The French firm "Sciaky" is extensively involved with friction welding. According to the information available, this firm published by middle of 1968 results of several technical studies and developed 7 types of machines (however, none of these machines have been built at that time).

At the same time, a series of firms "Toyota" Japan, AMF in USA, "Steelweld" in Great Britain, KUKA in West Germany, Welding Institute in Glivice, Poland and others marketed friction welding equipment. Without going into detail we feel it is useful to analyze basic features of the friction welding equipment developed by foreign firms and compare with the features of the Soviet equipment. Fig. 66-71 show photographs of some foreign equipment. Table 13 summarizes basic characteristics of friction welding equipment developed abroad.

Unlike Soviet machines, most foreign machines are designed for reduction of unit power and, consequently, reduced productivity of the machine. All foreign machines have a wide range of

rotation speeds and therefore a wide range of welding cross sections. Such universality of each machine together with a relatively small productivity are characteristic of most foreign machines. One can draw the conclusion that this equipment was

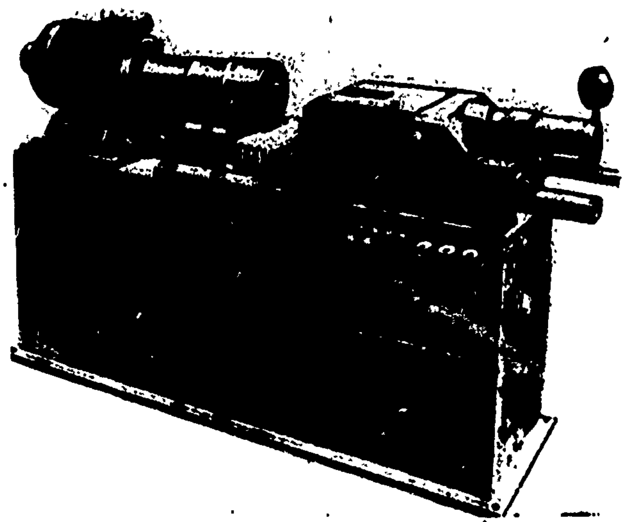


Fig. 66. Semi-automat ZTa-10 for welding of cutting tool parts (Poland) (43.74).

designed for low volume production and for operation at relatively small plants.

The Soviet machines are less universal but more powerful. They are designed to be used in large production plants in mass production. Thus, the main difference between the Soviet and the foreign friction welding machines is determined by their purpowe with different character and organization of production which are characteristic of countries with different economies.

Another feature of the foreign machines is that they tend to be designed for welding of micro-parts (see p.13) with a cross

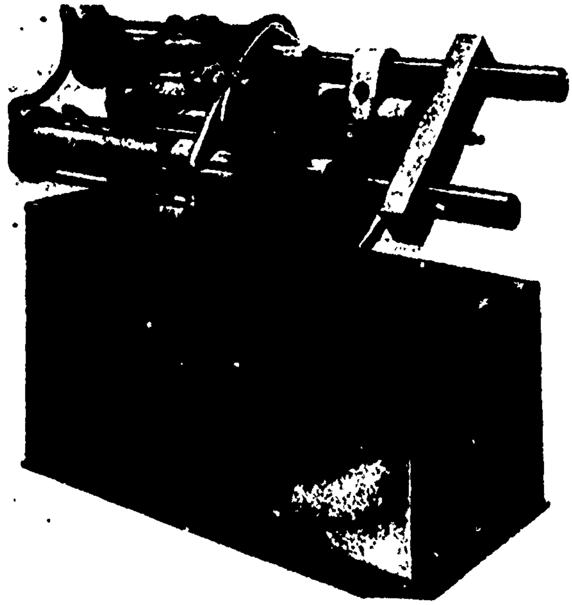


Fig. 67. Friction welding machine made by firm "Gatwick Friction Welding" (Great Britain).

Fig. 68. "Steelweld" FS2 type machine (Great Britain).

Table 13

Characteristics of Foreign Friction Welding Machines

Firm (Country)	Machine Type	Maximum Cross Section of welding parts in mm^2	Power: Full in kw	Power: Unit in kw/mm^2	Rotation Speed in RPM	Number of steps in speed change	Maximum Axial Force in tons.	Productivity Weldings per hour.
'Black Friction Welding' (Great Britain)	FWH-3	300	3.7	12	—	—	—	—
	FWH-10	760	11	15	—	—	—	—
	FWH-20	1700	37	22	—	—	—	—
	FWH-28	2200	75	34	—	—	—	—
'Gatwick Friction Welding' (Great Britain)	—	300	11	36	2000—4500	—	7	120
'Rouland' (Great Britain)	—	1600	18.5	11.5	1000/1500/2000	3	40	—
'Steelweld' (Great Britain)	FS-10	400	6.5—11.0	27.5	1500/2000/3000	3	4	300
	FS-1	800	13—21	25.0	1000/1350/2000	3	8	240
	FS-2	1600	20—32	20.0	750/1000/1500	3	16	180
'John Tompson' (Great Britain)	12ton	800	15	18	—	2	12	No Data
	40ton	2600	—	—	—	2	40	
	100ton	6450	—	—	—	2	60	
Welding Institute (Poland)	ZTa-10	700	13	18.5	1450	1	5	120—180
'American Machine and Foundry Co.' (AMF, USA)	15—4	1100	11	10	500—10 000	Smooth Regulation of speeds. 8	9	No Data
	75—A	6250	55	9	650—4000		60	

Table 13
(con't)

Characteristics of Foreign Friction Welding Machines (con't)

Firm (Country)	Machine Type	Maximum Cross-Section of welding parts in mm²	Power: Full in kw	Power: Unit in kw/mm²	Rotation Speed in RPM	Number of steps in speed change	Maximum Axial Force in tons.	Productivity Weldings per hour.
AMF (USA) (Inertial Welding)	10C	625	11	16	3000 Maximum	10	10	100
	30A	1900	15	8	3500	10	30	60
	60A	3750	15	4	1500	10	60	40
KUKA (German Federal Republic)	RS6000	390	12	31	1500/3000	2	6	--
	RS15000	1000	30	30	1500/3000	2	15	--
'Toyoda' (Japan)	FW-15	180	4	22	2750--5500	—	2	60
	FW-30	700	8	11	750--3000	—	7,5	60
	FW-60	2800	16	5.5	500--2000	—	17.0	60
'Sciaky' (France)	F-350	314	5.5	17.5	1000--4800	Smooth Regulation of speeds.	4 0	60
	F-700	700	11	16,0	2400--4200	4	7,0	80
	F-1150	960	11	11,5	2500--4000	4	6,0	50
	F-1700	2800	22	8,0	500--2000	4	17,0	50
	F-3500	5650	37	6,5	500--1750	4	20,0	30
	F-1200	1250	40 (hydraulic drive.)	8	4000 Maximum	—	12	100
	F-4000	5000	Same.	—	20.0	—	40	—

Fig. 69. "Toyota" FW60 type machine (Japan).

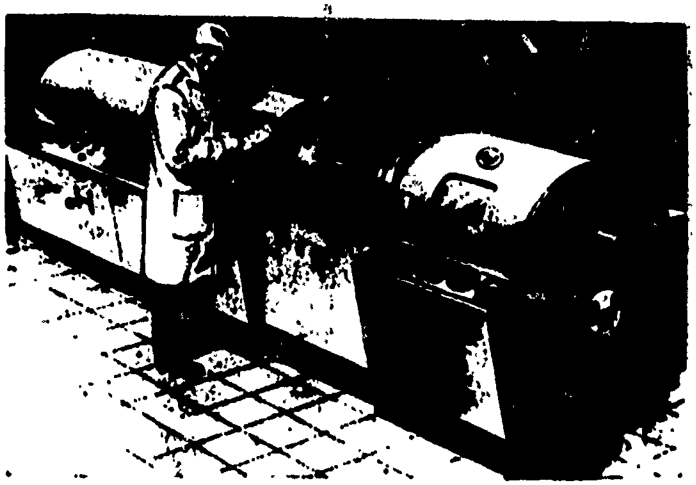


Fig. 70. AMF model 75-A machine (USA).

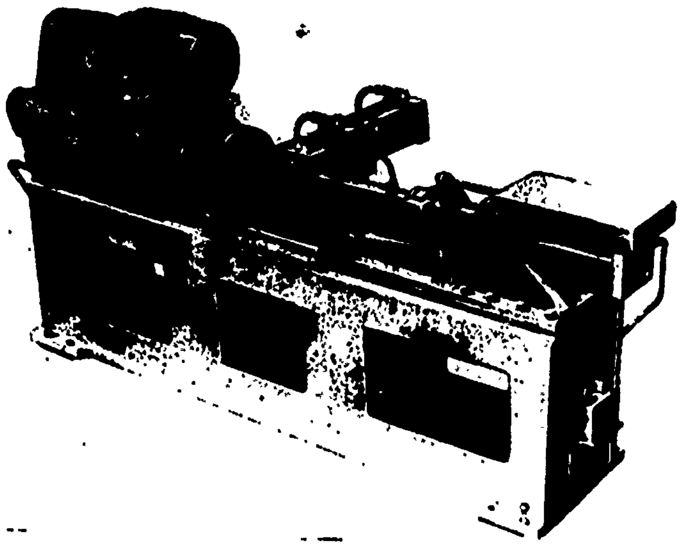


Fig. 71. "John Tompson" 40 ton machine
(Great Britain).

section up to 0.05 sq. mm but using the same values of linear speeds (1-1.5 m/sec) which we recommended.

Most foreign machines use hydraulic power drives whereas our machines utilize, in most cases, pneumatic-hydraulic power drives. It should be also noted that almost all foreign machines are designed for welding of relatively short pieces. Therefore, these machines are designed by the scheme where one part rotates and the other moves along the axis.

38. Equipment for Inertial Welding

Not so long ago a "new welding method" was described in the American technical literature, the so-called inertial welding. It was called "new" apparently because of patent considerations. Basically, the inertial welding is one version of friction welding. It is different from the common friction method only because the mechanical energy necessary for welding is converted

from the electrical energy not in the immediate welding zone but is accumulated in the flywheel of the machine. This feature of the inertial welding equipment makes it possible to solve uniquely some problems in technology and design of machines.

The inertial welding process of previously clamped parts begins with the comparatively slow rotational acceleration of the machine flywheel. A reserve of kinetic energy E_k is stored during rotation. The magnitude of E_k can be determined from the known equation

$$E_k = \frac{J\omega^2}{2} \qquad (42)$$

where J - energy moment of the flywheel

w - angular velocity of the flywheel rotation.

When the accumulated energy $E_{k\ max}$ reaches the magnitude for welding of the given parts and the rotational speed is

$$\omega = \sqrt{\frac{2E_{k\ max}}{J}}, \qquad (43)$$

a special device reacting to the magnitude of rotation goes into operation and sends a command to the electromagnetic clutch. The machine shaft is connected to the flywheel and begins to rotate together with it. Thus the welding parts are brought into relative rotation. If their faces were pressed against each other, then heat emission starts in the butt.

The moment of rotation M_t in the butt is (if one does not count losses due to friction in the machine) the only braking moment in the system and, consequently, it determines the braking path (coasting) and the duration of braking because the friction work can be expressed as

$$M_t\alpha = k\frac{J\omega^2}{2}. \qquad (44)$$

Thus, the braking path α depends on the magnitude of the reserve energy and on the moment M_t. The braking time during welding of a given pair of parts (and the entire heat emission pro cess) is defined by two parameters: the initial rotation speed of the flywheel and the compression force on the parts during welding.

As can be seen from Fig. 72. the heating time during inertial welding is significantly lower than during ordinary friction welding. To increase the heat emission (reduction of the braking path)

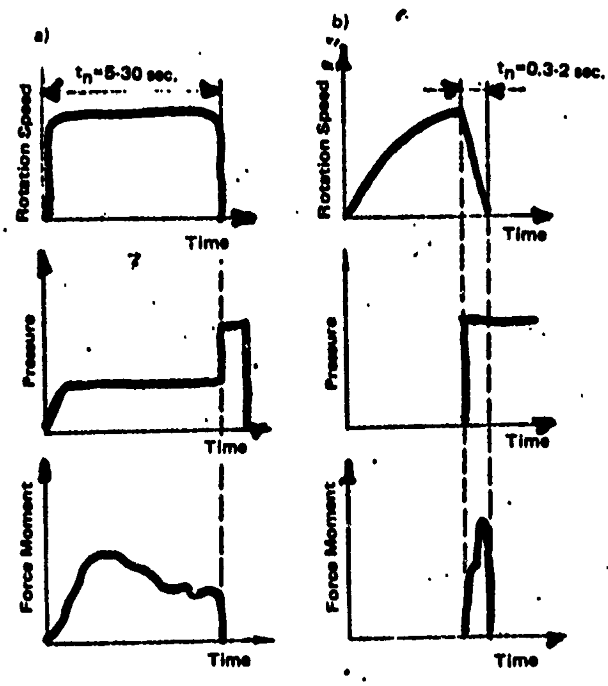


Fig. 72. Inertial welding process cyclograms (b) and ordinary friction welding (a).

the axial force should be comparatively large in such machines.

For instance, at a level of magnitude usually accepted for peening pressure (however, a large increase in pressure is not desirable as in ordinary friction welding).

The energy necessary for welding of a given pair of parts can be predetermined experimentally. The precision assignment of the energy stored in the flywheel is sufficiently convenient because of the relatively low power of the drive and the slow and smooth increase in the rotation of the flywheel.

There are no machines for inertial welding in the Soviet Union. Thus, the comparison of the properties of the inertial welding process and the corresponding equipment can be done only using literary sources.

The unconditional advantages of the inertial welding are: the reduction in the number of basic process parameters from four to two, this is convenient when selecting the welding regimes;

the reduction in power consumed by the machine when compared with the usual machines for friction welding due to accumulation of the energy in the flywheel.

However, the inertial welding has serious deficiencies:

1. It can insure a high uniformity of the welding joint quality only when faces of the welding parts are prepared in identical manner before welding. Fats, contaminations, burrs, different purity in the processing of faces will have an effect on the uniformity in the properties of the welding joints (anyway, a certain flywheel energy will be transmitted into the butt as heat but part of it may be dissipated for burning out of fats, wearing down of burrs; thus, the period of heat emission depends on the purity of the surface before welding).

2. The short heating period also causes small magnitude of upset; this requires a preliminary (before welding) careful machining of the faces on the lathe to insure the perpendicularity of their rotation; one of the important advantages of the ordinary friction welding is that no preliminary processing of the friction faces is required. In inertial welding, the cutting of parts is not permissible.

3. Despite the short heating time, the productivity is hardly higher than for friction welding because the machine time also includes the acceleration of the flywheel.

It should be added that the process is conducted at variable (falling) rotational speed and, consequently, is ended with wear of the friction surface in depth (characteristic of small speeds). This cannot contribute to improvement of the structure and texture of the metal in the butt region and may lead to defects.

It is possible that the above mentioned deficiencies of the inertial welding process proposed by AMF forced this firm to deviate from the original scheme of this process.

In reference (65) AMF advertises an inertial machine of different principle of operation. This machine (Fig. 73) has a flywheel which is accelerated to the established value of the rotational speed during pauses between weldings. After the parts are installed in the clamps and their faces brought together (button control) the machine shaft is connected with the help of a multi-disc, electromagnetic clutch to the flywheel and the energy stored in the flywheel is dissipated for heating the welding parts.

The heating process during welding ceases in that instant

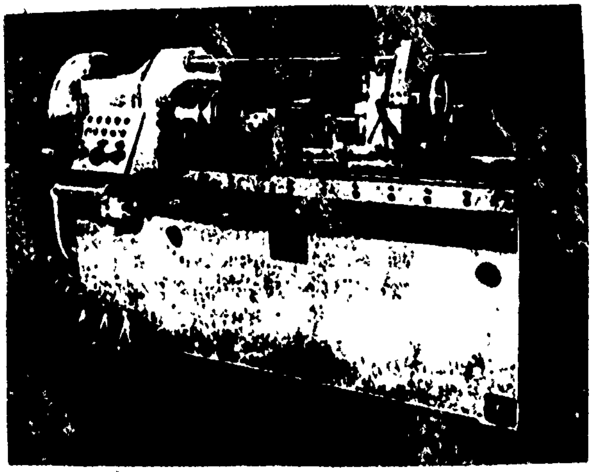


Fig. 73. AMF inertial welding machine (USA). Model 30A.

of time when the speed of the flywheel is reduced to one of the tne previously determined rotation speeds (the required one is selected with the help of a switch). When the flywheel reaches the predetermined final speed (ωt) a signal from a tachogenerator which continuously controls the rotation speed (and, consequently, the magnitude of the kinetic energy remaining in the flywheel) is received to disengage the shaft from the flywheel by the multi-disc clutch. The heating ceases and the flywheel connected with the electrical motor gains speed until it reaches the predetermined magnitude (ω_{st}).

Thus the energy dissipated as heat is equivalent to the difference in the kinetic energies of the flywheel

$$E_s = E_{st} - E_f = \frac{I}{2}(\omega^2{}_{st} - \omega^2{}_f), \tag{45}$$

where E_s - energy equivalent to the amount of heat emitted in the welding parts;

E_{st} - initial energy of the flywheel corresponding to the established speed of its rotation;

E_f - the flywheel energy at the moment of its disengagement from the shaft.

The magnitude of the energy consumed during welding may be varied (see above) by changing the magnitude of ω_f (and, consequently, E_f) and also by changing the inertia moment of the flywheel whose design permits to add or subract discs. Because the instant of the stoppage of heating (disengagement of the shaft from the flywheel) is fixed by the electrical circuit the same command may be used for the signal to increase pressure. The machine, consequently, makes it possible to perform the process with peening.

Thus, the second version of the inertial welding machine has following control parameters: E_s - welding energy (final speed of rotation of flywheel); p_n - heating pressure; p_{np} - peening pressure.

Compared with the traditional machines for friction welding, this machine, apparently, has certain advantages: the number of process parameters is reduced from four to three; the power and the energy consumed is reduced.

At the same time this machine has advantages over the first machine for inertial welding. It does not have deficiencies of the first machine: lowering of productivity of the welding process, lowering the quality of the welded joint and its uniformity.

However, this machine has substantial deficiencies: only after careful preliminary processing of the friction surfaces of parts can this machine make satisfactory joints (strict

perpendicularity of the surfaces to the axis, absence of fats or dirt at the joining surfaces are required); the heating process during welding occurs at changing speed and is ended at low speeds; this may cause defects in the butt metal.

An analysis of the properties of the machine leads one to believe that the inertial welding is expedient in organizations with well-organized preparation of parts for welding and mainly for welding of parts with large cross sections because in this case the dominating role is played by the low power of the drive and low line power consumption.

Apparently, the same conclusions were reached by the originators of the inertial welding because AMF together with the new inertial machines continues to produce and advertise machines for traditional friction welding. Machines which accumulate energy in their flywheels are used by the firm predominantly in the design of large units.

Table 13 lists the characteristics of machines for inertial welding.

One version of the inertial welding machines was recently designed in Japan. It was discussed at the friction welding colloquium of XXI Congress of the Internal Welding Institute (Warsaw 1968) by Dr. Khasun and others.

The kinematic scheme of this machine is notable by the fact that both parts subjected to welding are clamped into grips which rest on bearing supports and can rotate. One of the clamps is driven from the motor, the other rotates freely in supports and has a flywheel. At the beginning of the process, because of the inertia of the flywheel, the second part does not rotate, at the

same time the first part rotates at the full rotational speed of the drive. Later, with the help of the friction forces in the butt the second part begins to rotate. The process of heat emission is continued until the relative speed equals almost zero. Thus, at the beginning of the process the heat emission rapidly grows because of the increase in the friction moment (as in the rodinary friction welding) and then it gradually is reduced as the second part picks up the rotation speed.

At the end of the process self-control in the intensity of heat emission occurs. This is the feature that basically distinguishes the Japanese machine from the American one.

Considering their characteristics it should be noted that the productivity of the Japanese machine is, apparently, lower than that of the American one. At the same time it is more complicated in design, because it is supplied with two shafts instead one. It should be emphasized that the process depends on the mass of both parts and that it is difficult to weld long parts on the Japanese machine. Its advantages are in self-control of the heat emission. Moreover, when necessary the process may take a sufficiently long time. In the Japanese machine the quality of the welded joint depends on the initial conditions of the process, including the method of preparation of faces for welding and its condition before welding, the same as in the AMF machine.

The Japanese inertial welding machine differs from the ordinary friction welding machines by the reduced number of basic process parameters and the complicated design.

Footnotes to Chapter IX:

[1]In very rare conditions, beltless drive is used in uniaxial arrangement of the machine shaft and the drive motor.

[2]Attempts at making such a drive were made, and were completely unsuccessful.

Chapter X

THE INDUSTRIAL APPLICATION OF FRICTION WELDING

It was mentioned in Chapter I that the friction welding should be used in the following cases:

during fabrication of parts with annular cross sections with stepped longitudinal profile (manufacturing by welding parts consisting of rods with different diameters instead of machining or forging from one piece);

during manufacturing of composite bi- or tri-metal part to save the rarer or more precious material;

when it is necessary (for instance because of the operation conditions of the welded part) to manufacture parts as composition from several materials, which often differ in their properties and are either welded with extreme difficulty or cannot be welded at all with the use of other types of welding;

in manufacturing of parts with complicated shape by combining the friction welding with forging, stamping, or casting.

It should be borne in mind that the friction welding equipment is comparatively complicated and expensive. Therefore, the maximum economic efficiency in using the friction welding is achieved in mass or serial production of relatively large batches of parts or groups of parts that do not require a significant readjustment of the machine. In these cases semi-automats (serial or special) and automats should be used. In separate or low volume production one should use friction welding machines which are simple and easily adjustable when changing from welding of one part to another.

To illustrate the possibilities of friction welding we present some instances of its use at the Soviet plants[1].

The manufacturing of the cutting tool. About half of the friction welding equipment in operation in the USSR is used for manufacturing of the end cutting tool (Fig. 74). The friction welding successfully replaced the electric resistance welding during production of drills of medium size at the Vilnius Drill Plant (automats MSTA-31 and semi-automats MF-327), at the Moscow

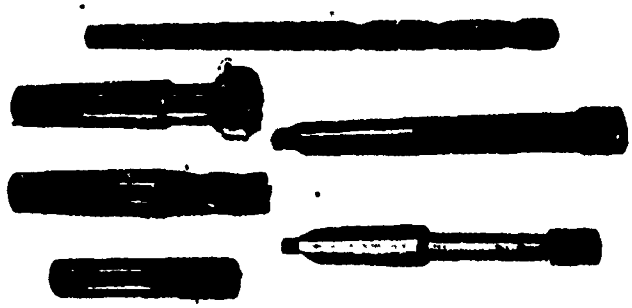


Fig. 74. Welded drills and cutters (steel R18 + steel 45).

plant "Frezer" (MF-327), at the Moscow Tool Plant (semi-automats MST-35, MST-41) at the Tashkent, Chelyabinsk, Orenburg, and other tool plants, and also in the tool shops of many large metal processing plants.

The economical efficiency obtained as a result of the use of friction welding in manufacturing tools is specified by the significant reduction in defect and labor (usually the welding defect is revealed during the finishing operation after polishing of almost finished tool) and very substantial savings of rare and expensive rapid cutting steel (see chapter VII).

When replacing the electric resistance welding by friction

welding in manufacturing of tools the monetary savings on the average (depending on the diameter of the welding parts and production conditions at a given plant) are 20,000 rubles for each machine during two months operation.

The expense to introduce the friction welding pays for itself in less than 6 months.

The manufacturing of measuring tools and the parts of the rotating center for lathes (Kalibr Plant, Moscow). Smooth and threaded (Fig. 75) calibers (probes) made before from expensive steel SHKH by forging method are shown.

After introduction of friction welding (Fig. 76 b) the part is produced as a composite part: using the automat MSTA-32 the tail made from 45 steel is welded to the operating part made from SHKH steel. It results in the saving of the expensive chromium steel and significant increase in the productivity.

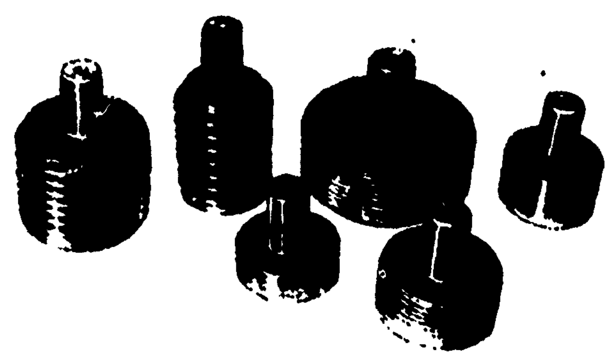


Fig. 75. Welded smooth and threaded calibers.

Using the same automats with insignificant changes one can accomplish the welding of center rollers for lathes (Fig. 77).

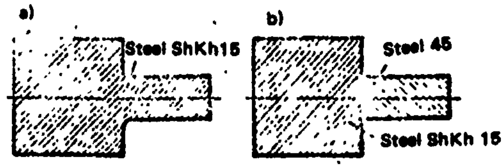


Fig. 76. Caliber production: a - old method; b - friction welding.

Previously, the rollers were machined from a whole rod after cutting out the part. The introduction of friction welding increased the number of operations: cutting of two rods and welding, but this reduced the labor time and significantly lowered the consumption of U8 steel (a large part of this steel was replaced by 45 steel).

As a result of the introduction of the friction welding at the Kalibr plant in 1964 in manufacturing of calibers and rollers the productivity of labor increased sharply, 200 tons of SHKH and U8 steel were saved, and heavy forging equipment was freed.

Moneywise, the economic effect was about 20,000 rubles for each of the three operating machines.

The manufacturing of parts of high voltage air switches at the high voltage equipment plant (Velikiye Luki). The welded-stamped T-shape parts of the switches are shown in Fig. 79.

Fig. 77. Lathe rotating centers.

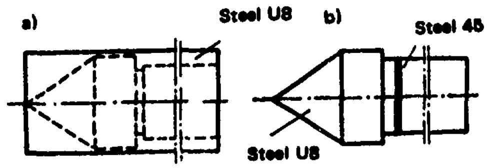


Fig. 78. Production of rotating center rollers:
a - old method; b - friction welding.

According to the old procedure (Fig. 80a), the plates were stamped by a compound stamp, the rod was machined and cut from the stock, the part was assembled from two parts and manually arc welded. After welding it was cleaned. The introduction of friction welding on the MST-31 machine (Fig. 80B) reduced the number of operations (stamping using an ordinary stamp, cutting of the rod, friction welding) and the labor. Parts of 16 different sizes are produced. The annual saving is 2500 rubles for each operating machine. The machine pays for itself in less than two years.

The production of parts of hydraulic and pneumatic cylinders for welding equipment ("Elektrik" Plant, Leningrad). A cycle consisting of seven operations (Fig. 82a) was required previously to join the piston with the rod (Fig. 81) with the help of semi-automatic submerged welding: the cutting of two pieces, machining of one of them, machining of the other, welding from two sides, cleaning.

After induction of friction welding in 1959 (Fig. 82b), the number of operations was reduced to three (cutting of the two parts, friction welding).

A big gain was achieved in the productivity, and the

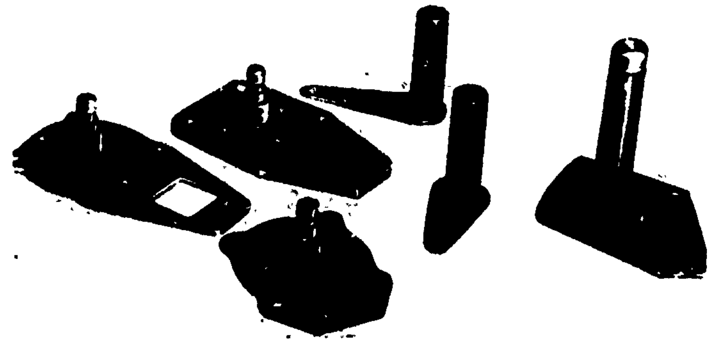


Fig 79. Welded-stamped parts of high-voltage equipment.

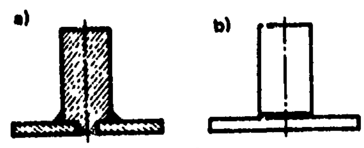


Fig. 80. Production of T-shape parts of high-voltage equipment; a - old method; b - friction welding.

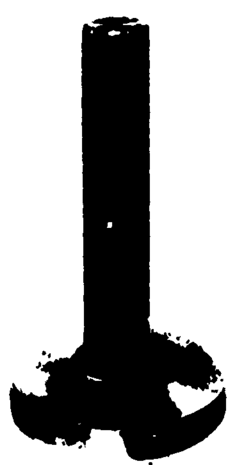


Fig. 81. Piston welded with rod.

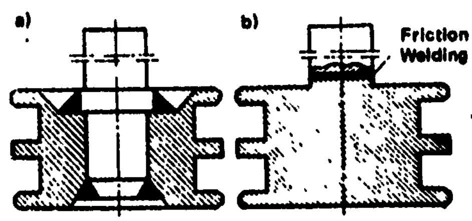


Fig. 82. Production of piston with rod. a - old method; b - friction welding.

consumption of the welding wire and flux was lowered. Parts of 30 different sizes are produced. The annual saving for one machine (MST-31) is about 3500 rubles.

At present time the plant introduced a second, general purpose machine MST-51 for welding of analogous parts with larger cross sections.

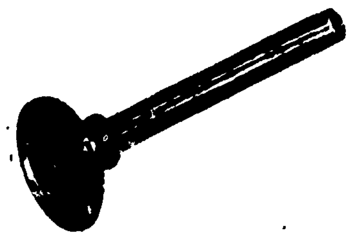


Fig. 83. Welded-stamped valve for internal combustion engine.

<u>The production of internal combustion engine valves</u>. The welded-stamped piece is shown in Fig. 83.

Before using friction welding, the part was stamped in its entirety, made from expensive steel by cutting and hot stamping.

The friction welding of this part consists of a larger number of operations (cutting of the two pieces, stamping of the dish, friction welding, flash removal). However, the expense for introducing a new method paid for itself with profit by reducing the consumption of the heat resistant steel, the increase in the

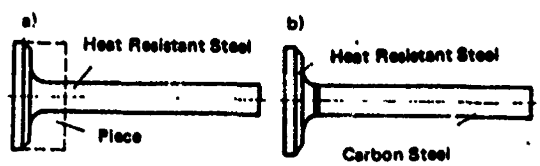


Fig. 84. Production of valve: a - old method; b - friction welding.

productivity and the freeing of the heavy forging equipment.

The production of turbocompressor rotors for diesel engines. (Fig. 85). Up to now, the wheel (austenite steel) was welded to the roller (perlite steel) using electric arc welding with special austenite electrodes.

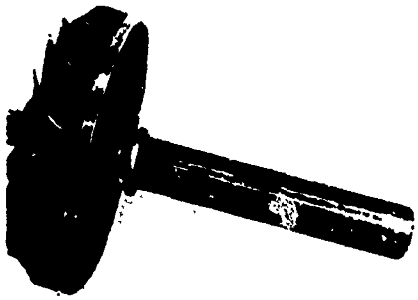


Fig. 85. Welded-cast turbocompressor rotor for diesel engine.

Despite the small diameter of the part at the welding location (45-60 mm) several phases were required during welding. There were also significant welding defects.

The developed friction welding technology for this joint made it possible to increase the productivity, to make the process cheaper, to make the austenite electrodes unnecessary, and to reduce the defect to zero. The use of friction welding made it possible to mass-produce the rotors at several plants and tus to solve an important economic problem.

The use of friction welding in tractor building (Minsk Tractor Plant). The friction welding began to be introduced in

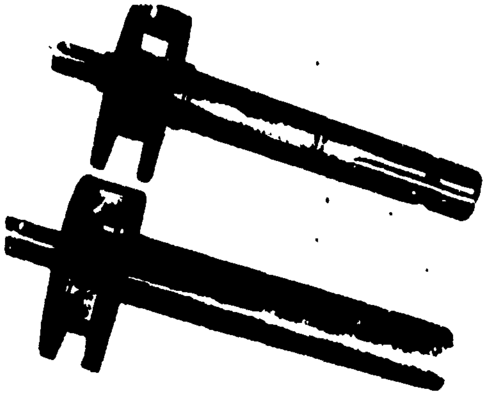


Fig. 86. Carrier of the power take-off shaft; welded-cast version using friction welding.

this plant in 1960. At present time, ten friction welding machines operate continuously at this plant. Each one is a special purpose machine designed for welding of parts of one type only. Friction welding is used in welding of:

a. very important parts of the steering control;

b. carrier of the power take-off shaft (Fig. 86) shows the welded piece and the complete part); the use of friction welding made it possible to solve the design of this part uniquely and very efficiently as a welded-cast version; the annual savings for friction welding of this part is 30,000 rubles;

c. the connection of the power take-off shaft with the crown gear (Fig. 87) the annual savings is about 30,000 rubles;

Fig. 87. Tractor power take-off shaft; friction welding.

d. angle brace fork (Fig. 88); the use of welded-forged construction of this part instead of forged made it possible to simplify its production and to reduce cost, to free heavy forge equipment, and to lower by several factors the labor needed for producing this part, the annual saving is more than 15,000 rubles annually.

The first part to be friction welded at the Minsk Tractor plant was the gear shift lever. Because of the cleanliness of friction welding the friction welding machine could be placed in the mechanical processing shop. It was possible to eliminate

the interplant transportation of the parts into the welding shop and back. This alone saved 7000 rubles annually and almost paid for the expense of producing the machine.

It is important to note that during almost 10 years now the plant had no defects in welding during production of various, including important parts.

The production of bolts with welded-on heads (Fig. 89). In many plants the friction welding is used for production of bolds.

Fig. 88. Angle brace forK :welded-forged version using friction welding.

The welded bolt has no dificiencies of the forged bolt. At the same time it has all the advantages of the machined bolts. It is made in three operations: the cutting of two pieces and welding; the flash is removed during cutting of the thread.

Fig. 89. Bolt body and head friction welded.

The production of large bolts using this method is most efficient because of the freeing of the forging equipment. The economic efficiency of using friction welding increases as the length and the diamer of the bolt body increase.

The manufacturing of bi-metallic parts made from steel and aluminum. The use of friction welding allowed the solution of one important technical problem, which could not be solved up to now by other means - the manufacturing of steel-aluminum bi-metallic compositions with continuous or tubular cross sections (Fig. 90).

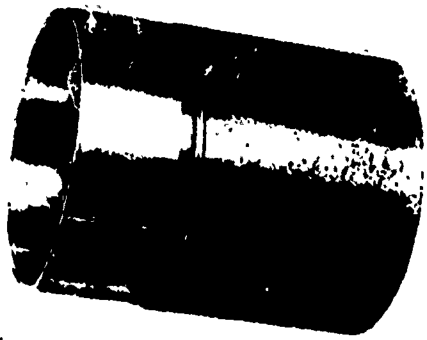


Fig. 90. Steel-aluminum tubular transition piece (friction welding, flash removed); diameter - 90 mm, wall thickness - 4 mm.

Such bi-metallic transition parts allowed the materialization of joints in complicated structures consisting of steel (low carbon steel, stainless or heat resistant steel) and aluminum (often aluminum alloys sub-assemblies. Other methods are used to weld these parts into the structure (steel with steel, aluminum with aluminum). The friction welded bi-metallic parts completely meet the increased requirements of the welded joint as far as its strength and seal capacity. At present time, these parts are made at several plants. Significant technical efficiency was accomplished. However, a numerical value cannot be determined because there are no bases and analogues for comparison.

Apparently, sufficient number of examples were cited to convince one of the technical and economical expediency of friction welding use in metal processing organizations of different branches of industry.

However, there are numerous organizations and enterprises where the designers are meek in applying friction welding. Especially, it is true of automobile industry. This was proved by the English firm "Steelweld" which advertises four types of machines for friction welding of various parts of an automobile beginning with the gear-shift lever, gears, engine valves and ending with the universal joint, rear bridge and steering wheel parts.

The Firm "Steelweld" designed special automated equipment for friction welding which is used successfully by Ford Motor Co.

In connection with this it is useful to know that friction welding was introduced successfully on a world-wide scale in tractor building, automobile building, in production of the internal combustion engines, in tube production, rocket building, structural industry, agriculture machine building, electrical and power industries, machine building and many other branches of production.

During the 13 years which passed from the actual inception of friction welding VNIIESO (most important Soviet organization in development and implementation of friction welding) and other Soviet organizations conducted productive research and development and introduced successfully friction welding into the industry. A basic theory of the process was developed, a general technology was worked out, special and general purpose equipment was designed and its serial production organized.

Following the Soviet Union other countries began to introduce friction welding: Czechoslovakia, Japan, USA, Poland, German Democratic Republic, Great Britain, France, Federal German Republic and other countries. These countries also conduct studies in perfecting the friction welding and its industrial use. However, in the volume of application these countries are far behind the Soviet Union.

However, despite the successes achieved in the development of friction welding, there are unsolved technical problems. A lot of work has to be done in the design of equipment, in the study of processes close to friction welding, which utilize heat emission and heating during friction.

The work on such theoretical problems as the study of the mechanism of welded joint formation in friction welding, the creation of engineering methods in selection and design of welding regimes according to predetermined properties of the welded joint, and the study of conditions for weldability by friction of new materials in different combinations should be continued in the comming years.

Not less immediate are problems in creation of newest friction welding machines and, in connection with this, the development of new kinematic schemes for equipment and the development of typical sub-assemblies for special purpose equipment. This will require the development of the necessary equipment and the determination of requirements of special purpose machines if some parts cannot be welded on the general purpose machines.

The more organizations and specialists take part in this useful work for the country, the greater the effect will be.

Footnotes to Chapter X:

[1]At present time, the friction welding is successfully used in more than 200 Soviet plants.

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